ISSN 2094-2516

Department of Science
and Technology

DOST
Science Education Institute

ENGINEERING RESEARCH & DEVELOPMENT FOR TECHNOLOGY (ERDT)

4th ERDT Conference

"Charting the R&D Roadmap of the Philippines"

February 19, 2010
Sofitel Philippine Plaza Manila
...as Blvd., Pasay City

ENGINEERING EDUCATION IN THE 21ST CENTURY: TOWARD AN INNOVATION-DRIVEN AND SUSTAINABILITY-CENTERED ENGINEERING DESIGN

Joel L. Cuello, Ph.D.
The University of Arizona, Department of Agricultural and Biosystems Engineering
507 Shantz Building, Tucson, AZ 85721, U.S.A., cuelloj@email.arizona.edu

INTRODUCTION

The world of the 21st century is one whose national boundaries have become porous and collapsible in many respects, but most especially in the economic sense -- allowing the linking together of local and national markets into one vast global marketplace. All this has been made possible by prodigious advances in communication, transportation, computer technology, the Internet, and with the widespread dispersion from the developed to the developing world of best practices in free-market economics, meritocracy, the rule of law and, indeed, in innovations in engineering and the sciences. Today's global marketplace is dominated and defined by China as the Factory of the World, by India as the Service Center of the World, and by the United States as the Innovator of the World. With the exception of a handful of oil-rich nation-states, the foregoing three economic archetypes, or their combinations, largely encompass the economic aspirations of all countries in the world today.

One of the notable accomplishments that the linking together of markets all over the world has achieved is the enabling of developing nations to fully enagage and participate in the competitive global economy, thereby galvanizing their development through unprecedented economic growth -- and consequently lifting millions of their people out of poverty within a generation. As a direct result of globalization, for instance, China's middle class which now comprises fewer than 100 million people is expected to jump to 700 million by 2020. India's middle class comprised 50 million in 2006, but is projected to jump to 583 million by 2025. Indeed, within a decade, nearly 80 percent of the world's middle-income consumers will live in nations outside the currently industrialized world. And by 2045 China will become the largest economy in the world, with an estimated real GDP in 2050 of $50 trillion, followed by the U.S. with $47 trillion and then by India with $32 trillion. Thus, developing nations that participate competitively in the global economy succeed and realize economic development and advancement.

It is noteworthy, however, that China and India have been able to exploit to their enormous advantage the competitive global economy because both nations have a lucid grasp of what the interconnected global economy is all about -- that is, that it is fundamentally based on knowledge and, specifically, on the creative translation of knowledge into value. For sure, China and India's low-wage work force is an indispensable factor to their economic successes, but the innovative knowledge-based value that they create and offer to the world -- high throughput manufacturing in the case of China and high-quality IT-based services in the case of India -- constitutes the true underpinnings of their unprecedented successes. Thus, while the economic ascent of nations has always been historically founded on knowledge creation and the translation of knowledge into value, this fact has never been more manifestly clear than it is today in this competitive and interconnected global economy.

All of these bring into sharp focus the primacy of engineering education in the knowledge-based global economy. Indeed, as a discipline and as a profession, engineering by definition is the creative translation of knoweldge into value. More precisely, engineering -- via the engineering design process -- is the creative translation of the knowledge of science, mathematics and existing technologies (and without the exclusion of the knowledge of aesthetics, art, literature, etc.) into value, which is defined as benefit at a given cost.

Thus, as a powerful knowledge-based tool that both corporations and nations employ to create and deliver sustained value to the global marketplace, engineering is simply indispensable in the globalized world of the 21st century. Indeed, a quick survey of the 20 greatest engineering achievements of the 20th century as compiled by the U.S. National Academy of Engineering -- which included electrification, the automobile, airplane, water supply and distribution, electronics, radio and television, agricultural mechanization, computers, telephone, air conditioning and refrigeration, highways, spacecraft, the internet, imaging, household appliances, health technologies, petroleum and petrochemical technologies, laser and fiberoptics, nuclear technologies, and high-performance materials -- attests to the inescapable fact that engineers, together with scientists and other knowledge workers and knowledge-based value creators, occupy the commanding heights of the knowledge-based globalized economy of the 21st century.

Consequently, engineering education has indeed become all the more important and challenging in the 21st century. The aim of this paper is to discuss the two most crucial principles that will inform and dominate engineering education in the 21st century in all its facets -- its goals, curricula, pedagogy, training, and professional practice. The two principles are: (1) an innovation-driven engineering design; and (2) a sustainability-centered engineering design.

DEFINITION OF ENGINEERING

[The following portions are adapted from the author's forthcoming book *Biological Engineering Design.*]

Engineering, at its core, is the creation of value using scientific knowledge as its enabling blueprint. "Value" is defined here as benefit per unit cost. Value that is created through engineering is embodied and delivered in the form of a product or process that performs a task or set of tasks that delivers the desired value. Thus,

Engineering design is the process of configuring a chain of functions which makes up a product or process performing a task or set of tasks that delivers a desired value or benefit at a certain cost.

For instance, various types of airplane (a chain of functions) have been designed to transport people by air (task) for safe and fast travel (value), dams (chains of functions) have been designed to store water and regulate water flow (tasks) for secured water supply (value), and the *i*phone (a chain of functions) has been designed to allow people to listen to music, connect to the internet and make telephone calls, etc. (tasks) and to be able to do so anywhere and at any time (value). This definition of engineering design applies to the engineering design of anything – a Boeing 747, a hybrid car, an *i*Pod, a skyscraper, a chemical process, etc. – and, indeed, applies to the engineering design process in every discipline of engineering.

Function Chain

The engineering design of a product (or process) consists of a configured chain of specific functions that, individually and collectively, enables the performance of a certain task or set of tasks intended for the design (Figure 1). Indeed, the configured chain of functions *per se* constitutes the product (or process). Formally, a function or function unit is defined as a module of physical, chemical and/or biological mechanism that performs a specific activity that, in combination with other function units, is essential to carry out the intended task(s) of the engineering design.

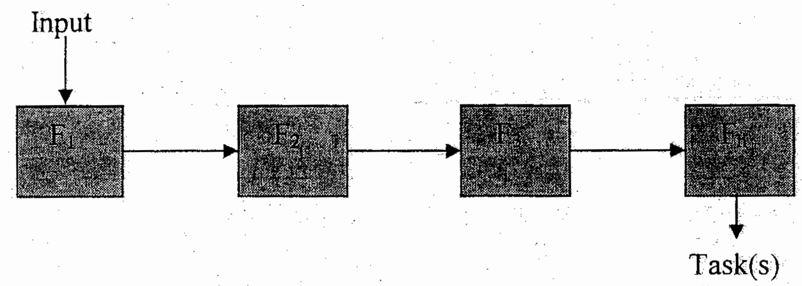

Figure 1. A configured chain of function units (F_1 to F_n), making up the design of a product (or process), enabling the performance of the specific task(s) intended for the design.

For a biosensor (Figure 2), for instance, whose primary task is to detect and quantify a specific substance (or analyte; e.g., blood glucose or blood cholesterol), the essential function units that make up its design include: (1) a biological detection element (e.g., enzyme, antibody, DNA, protein receptor), whose reaction with the molecules of the target analyte produces a physicochemical change; (2) a transducer (electrochemical, optical, piezoelectric, etc.), which converts the foregoing physicochemical change into a measurable signal (electric current, radiation, vibration, etc.); and (3) a signal processor/measuring device, which processes the signal and reports the measurement of the analyte. Thus, the design of a typical biosensor can be viewed as being composed of a configured chain of at least three essential function units, namely, a biological detection element, a transducer and a signal processor/measuring device.

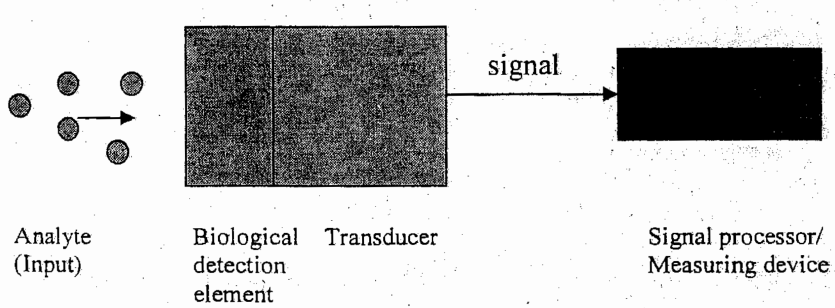

Figure 2. Design of a biosensor, showing its essential function units that enable it to perform the task of detecting and quantifying the concentration level of the substance (or analyte) that it is designed to measure.

Value Chain

The chain of functions that makes up the design of a product (or process) also yields a corresponding value chain. Individually, each function unit in the design adds to the aggregate value of the design (Figure 3). In the illustrative case of a biosensor, its biological detection element contributes such values as selectivity, sensitivity, recovery time, etc., to the overall biosensor design; its transducer contributes such values as accuracy, response time, etc.; while its signal processor/measuring device contributes such values as accuracy and readability (Figure 4).

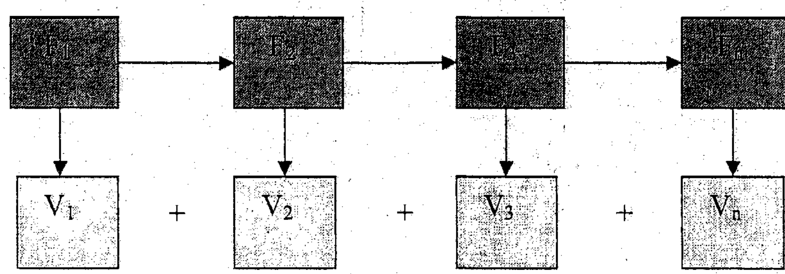

Figure 3. Partial value chain (V_1 to V_n) of a design arising from individual units of the design function chain (F_1 to F_n).

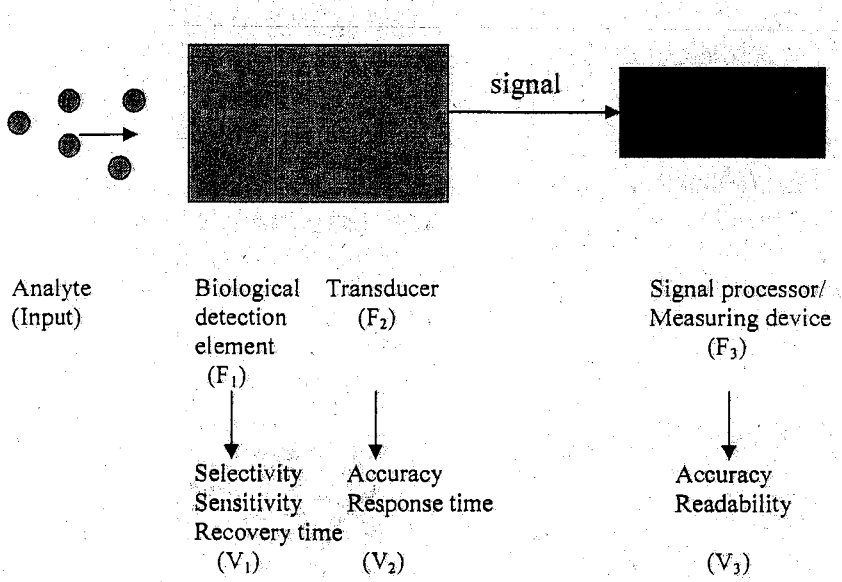

Figure 4. Partial value chain (V_1 to V_3) of a biosensor design arising from individual units of its design function chain (F_1 to F_3).

At the same time, the entire function chain of a design gives rise to values borne by the function units acting as a collective set (Figure 5). In the case of a biosensor, its collective function chain contributes to the overall biosensor design such values as weight, size, ease of operation, aesthetics, etc. (Figure 6). All the foregoing values, either generated individually by each function or collectively by the entire function chain, form the value chain of the design (Figure 7). Thus, the value chain of a design is the aggregate of the values borne by all of its constituent functions, acting individually and as a collective set. Conversely, the function chain that makes up a design gives rise, either through individual function units or through the entire function chain, a value chain for the design. Thus, engineering design may also be conceived of as configuring a chain of functions giving rise to a value chain.

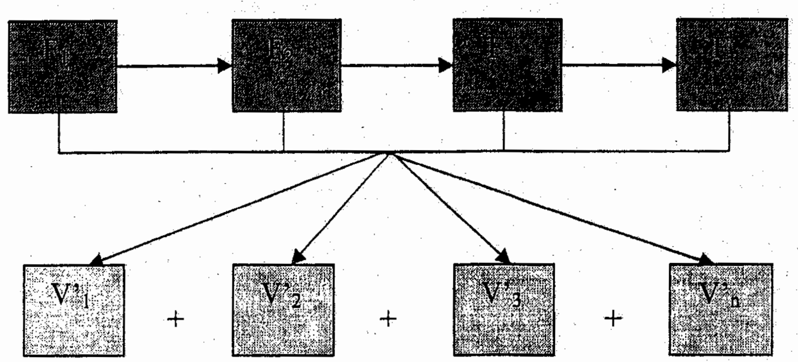

Figure 5. Partial value chain (V'_1 to V'_n) of a design arising from the collective set of functions constituting the design function chain (F_1 to F_n).

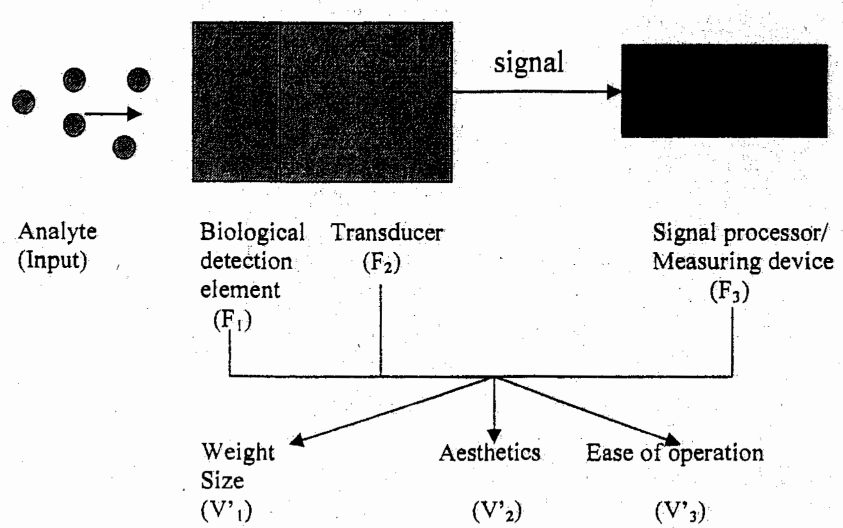

Figure 6. Partial value chain (V'_1 to V'_3) of a biosensor design arising from the collective set of functions constituting its function chain (F_1 to F_3).

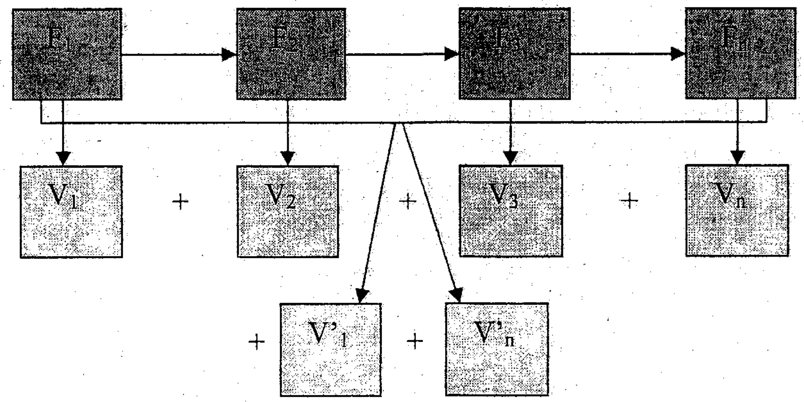

Figure 7. Value chain (V_1 to V_n plus V'_1 to V'_n) of a design arising from both the individual function units (F_1 to F_n) and the collective set of functions ($F_1 + F_2 + F_3 + F_n$) constituting the design function chain.

PRINCIPLE #1: INNOVATION-DRIVEN ENGINEERING DESIGN

[The following portions are adapted from the author's forthcoming book *Biological Engineering Design.*]

Given that engineering design is the creative translation of scientific knowledge into value (i.e., benefit at a certain cost) delivered through a product or process, today's knowledge-based global economy demands an engineering education for the 21st century that is firmly founded on the systematic learning and assimilation of the methods, techniques, habits, and culture of innovation, which is the creative translation of knowledge into value. Indeed, innovation in engineering demands a value-driven engineering design process.

The value-driven engineering design process treats the design of a product or process as being made up of a chain of functions which then generates a value chain. The design process *per se* is the configuring or reconfiguring of the constituent function units (or their components) and how they are combined together in a function chain (making up the design) so that the resultant value of the design is maximized.

It should be underscored that the mechanisms (physical, chemical and/or biological) constituting the various function units of a design must be described in sufficient details to enable a precise pin-pointing of the loci of the various design attributes in the function chain. Such details also provide the initial information that would suggest how the pertinent function units (or their respective parts or components) should be reconfigured to increase the created value of the design.

Design Value Analysis (DVA) is a quick and practical, yet powerful, tool that may be employed to evaluate the resultant value of a design.

Design Value Analysis (DVA)

Value Analysis (VA) was pioneered by Lawrence D. Miles at the General Electric Company in the late 1940s, and numerous improved and reworked versions, including those at the Xerox Corporation in the late 1960s and Functional Analysis (FA), have been put forward through the decades (Fowler 1990). Design Value Analysis or DVA is presented here as a method for charting and assessing the value chain of a design and how its aggregate or total value compares with those of others. DVA is a novel version of VA and is most closely based on Value Factor Analysis developed by SRI International in Silicon Valley, California (Carlson and Wilmot 2006).

Design Value Analysis is a method of quantifying the innovation, or created value, of a product (or process) relative to that of another. The design's innovation or created value is defined as design benefits per unit cost. Thus,

Design Value = (Design Benefits)/Cost [Equation 1]

Design benefits are generated by three classes of design attributes, including: (1) performance attributes; (2) convenience attributes; and (3) social attributes. Hence,

[Equation 2]

Design Benefits = f(performance attributes, convenience attributes, social attributes)

The individual attributes that make up each of the foregoing three classes of design attributes depend on the specific product (or process) being designed. For instance, for the biosensor design depicted in Figure 6, the biosensor's performance attributes would include selectivity, sensitivity range, accuracy, response time, etc. The biosensor's convenience attributes would include its weight, size/volume/portability, reagent requirements, and ease of operation. Meanwhile, the bisosensor's social attributes would include human safety/ergonomics, environmental safety, and aesthetics.

The design benefit contributed by an attribute is calculated as the product of the importance to the customer of that particular attribute and the rating achieved by the design for satisfying that particular attribute. Thus,

Design Benefit = (Importance-to-Customer Rating)(Design Rating)* [Equation 3]

Calculating the sum of the benefits produced by all the performance attributes yield the total performance benefits. Likewise, the total convenience benefits and the total social benefits are similarly calculated. Meanwhile, the total cost involved in determining the design value (Equation 1) comprises: (1) material cost; (2) equipment cost; and (3) labor cost.

Hence, the design value is calculated as,

[Equation 4]

$$\textit{Design Value} = \frac{a(\textit{Performance Benefits}) * b(\textit{Convenience Benefits}) * c(\textit{Social Benefits})}{\textit{Total Cost}}$$

where the coefficients a, b and c provide the relative weights among the three types of benefits constituting the design value. The values of the coefficients are dependent on the relative importance of each type of benefit for a specific product or process from the point of view of the specific target customers. Typical values include: a=1, b=1, c=1; a=2, b=1, c=1; etc.

DVA Spreadsheet

Table 1 illustrates the DVA spreadsheet for assessing and comparing the design values of two biosensor designs for a specific analyte. The four principal components of the DVA, namely: (1) the design performance attributes; (2) the design convenience attributes; (3) the design social attributes; and (4) the cost, are accordingly shown.

Table 1. Design Value Analysis for Two Biosensors for Measuring Analyte X.

	Importance to Customer[1]	**New Biosensor Design Rating**[2,3,4]	**New Biosensor Design Benefits**[5]	**Alternative/ Competitor Biosensor Rating**[2,3,4]	**Alternative/ Competitor Biosensor Benefits**[5]
Design Performance Attributes					
Selectivity	5	5	25	3	15
Sensitivity Range	4	4	16	3	12
Accuracy	5	5	25	3	15
Response Time	3	4	12	4	12
Recovery Time	3	4	12	4	12
Working Lifetime	4	4	16	3	12
Power Requirement	5	4	20	4	20
Total Performance Benefits			**126**		**98**
Design Convenience Attributes					
Weight	5	4	20	3	15
Size/Volume/Portability	4	4	16	3	12
Reagent Requirements	4	4	16	2	8
Ease of Operation	5	4	20	4	20
Total Convenience Benefits			**72**		**55**
Design Social Attributes					
Human Safety/Ergonomics	5	5	25	5	25
Environmental Safety	5	5	25	5	25
Aesthetics	4	5	20	4	16
Total Social Benefits			**70**		**66**
Cost					
Material	5	2	10	4	20
Equipment	5	3	10	3	20
Labor	5	2	10	3	15
Total Cost			**30**		**55**
Design Value[6]			**21,168**		**6,468**

[1]Importance to Customer Rating: 1 (least), 2, 3, 4, 5 (highest)
[2]Biosensor Rating for Design Performance and Convenience Attributes: 1 (worst), 2, 3, 4, 5 (best)
[3]Biosensor Rating for Social Attributes: [-5 (worst negative rating), 5 (best positive rating)]
[4]Biosensor Rating for Cost: 1(least costly), 2, 3, 4, 5 (most costly)
[5]Benefits = (Importance-to-Customer Rating)*(Biosensor Rating)
[6]Design Value = [(Performance Benefits) * (Convenience Benefits) * (Social Benefits)]/(Total Cost)

The second column of the DVA spreadsheet is for rating each design attribute or cost in regard to its importance to the customer. This is rated from 1 to 5, with "1" indicating "least importance to the customer" and "5" indicating "highest importance to the customer." Since

DVA evaluates the importance of various design attributes and costs to users/customers as well as judges how well a particular design formulates or satisfies a given attribute, DVA is best conducted by design teams rather than by individuals.

The third column (new biosensor design) and the fifth column (alternative or competing biosensor design) of the DVA spreadsheet (Table 1) are for rating or judging how well a particular design attribute is satisfied by a given design. To rate how well a performance attribute or convenience attribute is formulated or satisfied by a given design, the design with respect to that attribute is rated from 1 to 5, with "1" indicating "worst rating" and "5" indicating "best rating." For example, for rating the biosensors in Table 1 in terms of accuracy, one of the design performance attributes, a lower number rating would mean worse accuracy and a higher number rating would mean better accuracy. Note, however, that for rating the biosensors in terms of weight, one of the design convenience attributes, less weight would be more desirable than more weight. Thus, a lighter weight would correspond to a higher number rating and a heavier weight would correspond to a lower number rating. Similar reasoning applies to two other convenience attributes, namely, size/volume/portability and reagent requirements. Thus, the rule is that a more desirable (better) condition would receive a higher number rating, while a less desirable (worse) condition would receive a lower number rating.

In evaluating how well a design satisfies a given social attribute, the design is rated from -5 to 5, with "-5" indicating "worst negative rating" and with "5" indicating "best positive rating." A negative rating means that the design has a deleterious or damaging effect to health, safety or the environment, while a positive rating indicates that the design has an ameliorative or enhancing effect to health, safety or the environment. Meanwhile, the design cost is rated from 1 to 5, with "1" indicating "least costly" and "5" meaning "most costly."

The design benefit contributed by each attribute or cost is calculated using Equation 3, and is shown in columns 4 and 6 of Table 1. The total performance benefits, total convenience benefits, total social benefits, and total cost are calculated accordingly and, using Equation 4, yield the design value for each biosensor design. Table 1 shows that the design value of the new biosensor design of 21,168 is over three times that of the alternative/competing design of 6,468, representing a significant innovative improvement. The approximate rule is that the design value must be 2 to 10 times greater than that of the alternative or competing design to be worth pursuing. A quick inspection of the DVA spreadsheet shows that the new biosensor design gained significant innovative value over the alternative biosensor design mainly through the former's performance benefits (126 vs. 98), convenience benefits (72 vs. 55) and cost reduction (30 vs. 55). The social benefits of the two biosensor designs were practically the same (70 vs. 66).

Two important caveats need underscoring regarding the use of Design Value Analysis: (1) the calculated design value obtained through DVA is not absolute, but relative -- that is, with respect to those of alternative or competing designs. DVA nonetheless is desirably intuitive and, indeed, allows for the much needed direct comparison of relative values between different products or processes; and, (2) the design values for the various competing designs of a given product or process as calculated by independent engineering design teams, when compared directly against one another, must be done so with significant caution, making sure that the various teams' DVA spreadsheet variables are identical and that their criteria for judging the designs are markedly consistent.

Value-Driven Engineering Design Process

Since Design Value Analysis provides a comprehensive inventory of the positives and negatives of a design with respect to customer value, DVA constitutes a tool that makes it possible to re-imagine the engineering design process into one that is value-driven. The foundation for such a value-driven engineering design process rests on the mechanistic premise that each attribute that makes up a given product's performance attributes, convenience attributes and social attributes arises as a direct outcome of and can be directly linked to a chain of functions that makes up the product's design. Thus, a design can be viewed as consisting of a chain of functions which then generates a value chain. Moreover, configuring or reconfiguring the function chain that makes up the design in such a way that the resultant value of the design is maximized constitutes the value-driven engineering design process.

The various steps in carrying out the value-centered engineering design process, and the essential role of Design Value Analysis in the process, are depicted in Table 3.

Table 2. Steps for the value-driven engineering design process.
1. Identify the task or set of tasks that the design (product or process) is intended to perform. 2. Configure the necessary function chain making up the design to actually carry out the required task or set of tasks. 3. Establish the value chain of the design based on its function chain. 4. Perform Design Value Analysis (DVA) to determine the value of the design in comparison with an existing, alternative and/or competing design. 5. Maximize the value of the design by reconfiguring the constituent function units or their components needing improvement as indicated by the DVA. 6. Iterate DVA until optimal design based on created value is achieved.

Thus, the value-driven engineering design process provides a holistic view of engineering design, keeping engineers always cognizant of what is most important in the design process -- the knowledge-based creation and delivery of real value to the customer. Indeed, the value-driven engineering design process constitutes an effective engineering design method for professional engineers, and serves as an effective pedagogical tool of engineering design for engineering students.

As an engineering design method, the value-driven engineering design process is universal. In the long term, only a value-driven engineering design – which explicitly links the engineering design process to the creation and delivery of value to the marketplace and the public -- can deliver sustained innovative solutions to society, while further creating new opportunities for development and advancement for many countries in the globalized world of the 21st century.

PRINCIPLE #2: SUSTAINABILITY-CENTERED ENGINEERING DESIGN

[The following portions are adapted from the author's forthcoming book *Wonder of Sustainability: The Ifugao's 7 Universal Laws of Sustainable Design from the Ancient World.*]

The linking together of local and national markets across national boundaries into one thriving global marketplace tends to minimize political or military conflicts between participating nations since their engagement in the global economy produces significant mutual benefits. Nonetheless, in view of the continuously burgeoning global population as well as the growing population of high-consuming middle-income earners all over the world, a quietly developing and potent political conflict in the 21st century is the looming competition between nations for global resources – including water, food, land, minerals, petroleum, etc. – to satiate the demands for consumption of the thriving global marketplace. Thus, while the interconnected knowledge-based global economy demands an innovation-driven engineering design, a resource-voracious global marketplace also rightly demands a sustainability-centered engineering design.

While the practice of incorporating sustainability in engineering design is growing, sustainability is not embedded in engineering design as much, as widely, and as consistently as it should be. In part this is due to the lack of a clear understanding of the fundamental principles of sustainability in engineering design and, in large measure, due to a lack of a known and existing model or archetype of engineering design that explicitly and sufficiently exemplifies the principles of sustainable design.

The good news is that an archetype of sustainable engineering design exists and, indeed, has now been in existence and in continuous operation for at least 2,000 years. This archetype can be found in the Cordillera Mountains of the Philippines – the Ifugao's ancient rice terraces (Figure 8). Popularly known as the Banaue Rice terraces, the ancient terraces of the Ifugao people lie at an altitude of more than 1,500 m (4,920 ft), and stretches for 3,204 km (2,000 miles) if connected from end to end. The cascades of terraces, with stone retaining walls serving as dikes and walkways, were sculpted by hand along the slope of the mountains, and carries forest water down from terrace to terrace starting from an elevation of 1,800 m. Considered the oldest and most extensive rice terraces in the world, the Banaue rice terraces have been recognized both by the United Nations Educational Scientific and Cultural Organization (UNESCO) as a World Heritage Site and by the American Society of Civil Engineers (ASCE) as an International Historical Engineering Landmark on account of its undeniable engineering ingenuity which was executed approximately in the year 1000 B.C. using no more than the Ifugao people's hands, feet and rudimentary tools. In its 1997 commemoration of the Banaue Rice terraces, ASCE proclaimed that, "The civil engineering principles of hydrology, sustainable development and efficient use of water sources and irrigation are all embodied in the careful design of this remarkable ancestral land management program that has never been rivaled." Indeed, in contrast to the world's other ancient wonders and marvels of engineering -- which are "unmoving, dead and ancient monuments like the Pyramids, Taj Mahal, Borobudur, Ankor Wat and the Incan civilization" -- the Banaue rice terraces stand apart as a live engineering wonder (especially after rice is planted when it is green or just before rice is harvested when it is golden) that has been in continuous use and continues to sustain the Ifugao people without interruption for more than two millennia.

Figure 8. The ancient Ifugao rice terraces as archetype of sustainable design.

The Ifugao's Banaue rice terraces, constituting a true archetype of sustainable engineering design, exemplify seven fundamental laws of sustainable design.

1. Law of Availability – The Law of Availability prescribes that design, to be sustainable, must select input resources (material or energy) from resources that are readily available. The Ifugao's ancient terraces were designed using the available materials of mountain slopes, mountain soil, mountain rocks and mountain spring water, and using the available solar radiation for growing the rice as well as the conversion of existing potential energy into kinetic energy to deliver the spring water from the top of the mountain down from terrace to terrace. The application of the Law of Availability for sustainable design can be seen today in many innovative – and sustainable -- engineering designs, including the Venturi automobile, equipped with solar cells covering its rooftop plus a wind turbine and, thus, runs solely on wind and solar power.

2. Law of Harmony – The Law of Harmony mandates that design, to be sustainable, must be in harmony with its intended function and/or its environment. The Ifugao's ancient terraces were designed such that each terrace was sculpted following the natural contour lines of the Cordillera Mountains, achieving a simple yet elegant environmental harmony. Further, the cascade of terraces along the slope of the mountain allows for the simple delivery and conveyance of the spring water located on top of the mountain to all the terraces, that is, by simply guiding the water to flow down from one terrace to the next. This design enabled the Ifugao rice terraces also to achieve functional harmony. The application of the Law of Harmony for sustainable design can be seen today from the uncluttered design of the Google website for the ease and clarity of conducting a websearch (functional harmony) to Frank Lloyd Wright's architectural designs that blend seamlessly with their natural landscapes (environmental harmony).

3. Law of Knowledge – The Law of Knowledge prescribes that design, to be sustainable, must be based on solid fundamental knowledge of science, aesthetics, etc. The Ifugao's ancient terraces were designed following the scientific principles of hydraulics, enabling the Ifugaos over the millennia for instance to divert stream water for irrigation up to five to six kilometers (approximately three to four miles). All legitimate engineering designs today employ the Law of Knowledge for sustainable design.

4. Law of Reuse -- The Law of Reuse prescribes that design, to be sustainable, must reuse or recycle resource (material or energy) that serves as output by the design. Thus, the roots and stubs of the cut rice plants after harvest are mixed and incorporated into the terrace soil for soil conditioning and fertilizing in preparation for the next planting. The reuse of nutrients from algae biomass after extraction of biofuel oil for growth of a new batch of algae cells in photobioreactors would be an application of the Law of Reuse for sustainable design.

5. Law of Symbiosis – The Law of Symbiosis prescribes that design, to be sustainable, may incorporate the integral linking of two components such that each component both derives and supplies benefits from and to the other. The Ifugao's ancient terraces combine rice plants with mudfish in the terrace ponds. The mudfish wastes provide nitrogen and other nutrients to the rice plants and mudfish help protect the rice plants by feeding on insects and other pests. In turn, the rice plants supply photosynthetic oxygen and natural habitat to the aquatic environment of the mudfish.

6. Law of Peers -- The Law of Peers prescribes that design, to be sustainable, must benefit from the insights and inputs from peers. The Ifugao's design of their ancient terraces certainly did not originate from one single individual, but coalesced from the active and sustained exchange of ideas, information, skills and experiences by a whole community of Ifugaos even across generations stretching over at least two millennia. Today jetliners, encyclopedias, operating systems, mutual finds, etc., are being created and designed by teams numbering in the thousands and even millions over the internet.

7. Law of Community -- The Law of Community prescribes that design, to be sustainable, must be integrated into the daily life of the community. The Ifugao's ancient terraces not only supplies food to the Ifugao community, but also have become an intimate and integral part of the community's various social, cultural and religious practices. Today, Apple's iPhones have become an integral part of the daily lives of people in the developed world.

The Ifugao's ancient rice terraces, as an archetype of sustainable design, as well as the seven laws of sustainable design that they exemplify constitute an effective pedagogical tool of engineering design for engineering students and, indeed, as a reference touchstone or archetype of sustainable design for professional engineers, architects and other designers. The author is currently developing a certification system for sustainable designs based on the Ifugao's sustainable design of its rice terraces -- proven over millennia – and on the seven laws of sustainable design that they embody.

Thus, in the interconnected knowledge-based and resource-intensive global economy of the 21st century, engineering education has become all the more crucial and challenging. An engineering education that focuses on both an innovation-driven engineering design and a sustainability-centered engineering design will, indeed, be truly instrumental in delivering value to the global market place both in a dependable (since it is knowledge-based) and responsible (since it is sustainable) manner.

REFERENCES

Carlson, C.R. and W.W. Wilmot. 2006. Innovation: The Five Disciplines for Creating What Customers Want. New York: Crown Business.

Cuello, J.L. 2006a. Innovation Nation: Seven Principles for Training Engineers to be Quantum Leapers. Resource. June/July 2006.

Cuello, J.L. 2006b, Offshoring and the Local Ethics of Engineering. The Bent of Tau Beta Pi. Spring 2006.

Cuello, J.L. 2006c. "Engineering to Biology" and "Biology to Engineering": The Bidirectional Connection Between Engineering and Biology in Biological Engineering Design. International Journal of Engineering Education. 22(1): 28-34.

Fowler, T.C. 1990. Value Analysis in Design. New York: Van Nostrand Reinhold.

Friedman, T.L. 2006. The World is Flat: A Brief History of the Twenty First Century. First updated and expanded edition. New York: Farrar, Straus and Giroux.

Palmisano, J.P. 2006. The Globally Integrated Enterprise. Foreign Affairs. May/June 2006.

Dr. Joel L. Cuello is Professor of Biosystems Engineering at The University of Arizona, Department of Agricultural and Biosystems Engineering, Tucson, Arizona, U.S.A. Email cuelloj@email.arizona.edu.