DESIGN: TO ENGINEER IS TO CREATE

The glory of the adaption of science
to human needs is that of engineering.
(Hardy Cross, engineering professor and author)

Design, whether used as a verb to represent a process or interpreted as a noun to refer to the result of the process, is omnipresent in engineering and related disciplines.

Design as process pervades all of these disciplines and is their essence in all sectors of the economy. Broadly speaking, the design process—the root of engineering—begins with defining the requirements, that is, defining a need or describing a problem or opportunity, followed by logical thinking, applying scientific principles, developing alternatives, considering socio-economic-environmental effects, deciding on a course of action, and communicating the results in a manner that enables implementation.

While the process typically relies heavily on traditional means and methods, it may include innovative and creative approaches. The goal of design is quality.

The ultimate result of the design process – the fruit that grows from the root – is a useful structure, facility, system, product, or process. Electrical engineers design electrical power systems, control systems, telecommunication systems. Aeronautical engineers design aircraft and spacecraft, civil engineers design high-speed rail systems, chemical engineers design processes to convert raw materials into finished products, and mechanical engineers design hybrid automobiles. As a result of their design orientation, all engineering disciplines deliver functional results some of which are stunning and widely acknowledged while others are unnoticed or taken for granted. Essentially all engineering designs contribute to the quality of life for untold users.

Mathematics, natural sciences, humanities, and social sciences are the foundation of engineering. While being students and appreciators of that foundation, engineers go beyond, as a result of the design process, to develop plans for structures, facilities, systems, products, and processes useful to and sometimes aesthetically pleasing to society.

These plans are the root of the engineering process and the fruit is that which is ultimately constructed, manufactured, or otherwise implemented.

3.1 Design in the Context of Major Engineering Functions

Four Engineering Functions

- Participate, if not lead, in defining a need to be met, a problem to be solved, or an opportunity to be pursued
- Lead and manage the design process which ends with documentation, often plans and specifications, sufficient to bring to reality that which was designed
- Lead, manage, monitor, or otherwise participates in the necessary construction, manufacture, or other implementation of that which was designed
- Assist with the fruitful use, operation, and maintenance of that which was implemented

Interaction

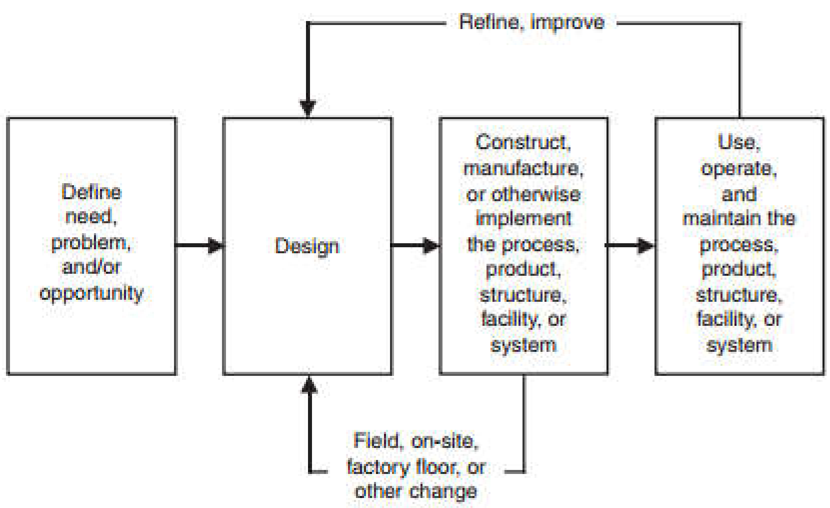

Figure 3.1 Engineers participate in these four major functions to meet needs, solve problems, and pursue opportunities.

Within a longer time scale, interaction occurs between the second and fourth functions shown in Figure 3.1.

Thoughtful engineers observe the use and operation of their designs; discover ways to improve those systems, facilities, structures, products, or processes; and integrate those improvements into their future design efforts.

At the micro level, interaction, more commonly referred to as iteration or trial and-error, is common within the design function. All but the most trivial designs typically involve numerous trial and error loops during which ideas are formulated, tested, analyzed, and changed or refined. ***As an engineering student or a recent graduate used to assignments and problems requiring analysis of existing entities and being asked to obtain unique and "correct" answers, you may find design to be somewhat unsettling.***

Rarely in practice is there a best or correct solution. Rather, the technical professional strives to arrive at a design that is within that "best" subset of all possible solutions.

"Back-of-the-Envelope" Sketches and Calculations

Conceptual, preliminary, or "back-of-the-envelope" sketches and calculations, based on an engineer's experience, are useful in the early stages of the design process.

Roughing out some alternative approaches, layouts, or configurations is likely to be more productive in the typically inevitable trial-and-error design process than seizing, at the outset, one possible approach and carrying its design forward in great detail. While quick "back-of-the-envelope" sketches and calculations by experienced engineers may be the creative impetus for the ultimate design, bringing that design to completion usually requires a major effort by a multi-disciplined team.

Design Phases

What has been referred to so far in this lecture as the design process is often an effort involving two or more phases.

For example, the preliminary design of the processes and controls needed to manufacture a product, documented in a report, is likely, after approval and with requested refinements, to be followed by a final design documented in the form of detailed plans or drawings and specifications suitable for project implementation. As designs progress through phases, the cost estimates become more accurate.

Each phase in the design process has primary emphasis or purpose. The preliminary design report is likely to focus on what to do to meet a need, solve a problem, or pursue an opportunity and explain why it should be done. In contrast, the final design plans or drawings and specifications typically show and describe, in great detail, how to do what has been recommended as a result of the preliminary design. What, why, and how thinking drive the design process, hopefully in a creative and innovative manner stimulated by tools and techniques.

Hard and Soft Results

In contemplating the ultimate results of the four engineering functions shown in Figure 3.1 you, as an engineering student or young practitioner, may think in terms of structures, facilities, systems, and products composed of metal, concrete, synthetics, and other substantive materials.

However, the illustrated process can produce "soft" results such as a computer model, a project management process, or a way to organize a technical organization to improve utilization of human and other resources.

The Disproportionate Impact of the Design Function

One reason the design function is so important, among the four engineering functions illustrated in Figure 3.1, is that while it accounts for a small fraction of the total project cost it is the primary determinant of the total project cost. That total cost is the sum of the cost of design; construction, manufacturing, and other implementation costs; and the subsequent and operation and maintenance (O&M) costs for a structure, facility, system, product, or process. The disproportionate or leveraging effect of the design process on total project costs and on the overall quality of the result is generally applicable across technical fields.

Design, or more specifically, the engineers and other technical professionals who do it, are the principal determinants of cost and quality. The importance of selecting those who will do a design, because of their impact on total costs, is addressed further in a later lecture.

3.2 Design In Terms Of Deliverables

The design process, as shown in Figure 3.1, typically results in the production of drawings and other written and visual information specific enough to be used by other individuals or organizations to construct, manufacture, or otherwise implement a structure, facility, system, product, or process.

The individual or organizational entity responsible for design is often not the same individual or organizational entity responsible for constructing, manufacturing, or otherwise implementing that which was designed. Conveying the essence of the “designer’s” creation to the “builder” in sufficient detail and with adequate understanding so that the latter can produce what the former intended is a monumental communication challenge.

The design process, especially in electrical engineering and similar disciplines, often results in the production of deliverables called bidding documents, which later become contract documents. Bidding documents typically consist of a package containing the following three components, each of which is discussed in the next sections:

- Drawings
- Technical specifications
- Non-technical provisions

Drawings

Drawings, which may also be called plans, graphically portray the type and arrangement of components that comprise the desired structure, facility, system, product, or process. That is, a set of drawings shows what is to be built, executed, or established and where. Given the typical complexity of design process results, a visual representation is essential. Many of us need to see something so that we can understand it, including physicist Albert Einstein who said “If I cannot picture it, I cannot understand it.” Drawings could include a few sheets to up to hundreds or thousands of sheets, depending on the size and complexity of the intended result. Drawings are sometimes produced manually, but are usually generated with computer-aided drafting (CAD) software.

Often, when a construction project is completed, the drawings used to guide the construction are updated to show changes made during construction. Such drawings, which are called record or as-built drawings, are subsequently useful to the owner when the structure, facility, or system is used, operated, maintained, and modified.

Technical Specifications

“Technical specifications [or just specifications] are written instructions and requirements that accompany construction drawings . . . In general, specifications contain all the necessary information that is not shown on the drawings." That is, drawings and specifications should not include duplicate information and, if they do, "the specifications take precedence"

Technical specifications, which ideally should be prepared by engineers involved in the project's design, could consist of a few pages or run on to hundreds or thousands of pages.

Specifications are typically developed by combining proven "boiler plate" text extracted and edited, as applicable and appropriate, from preceding or parallel projects or other standard sources, and carefully written original text peculiar to the design at hand.

Specifications are legal documents that should be written in a "simple and brief style" following a "say it once and say it right" and "when in doubt, spell it out" approach. Instructions for the contractor on a specific project are written in the imperative mode as in "***The contractor shall place concrete in lifts not exceeding 24 inches and compact each lift with mechanical vibrator equipment."*** Each word is important and the specification writer must combine technical understanding with great writing skill because, as they say, "the devil is in the details."

Specifications typically address a wide variety of technical and nontechnical topics. Some examples are: material requirements, testing requirements, installation or placement instructions, lists of materials or equipment, submittal and schedule requirements, safety and environmental protection needs, permits to be obtained, and coordination with other contractors.

Specifications, along with drawings and contract documents, are used by contractors in preparing bids, and if successful, in constructing the structure, facility, system, or product. The ultimate owner is typically interested in the specifications and drawings because they describe the end point in terms of what the owner will eventually use, operate, and maintain. Finally, engineers who will be involved in construction or manufacturing, use the specifications and other documents.

Non-Technical Provisions

The third and last portion of the deliverables typically produced by the design process may include one or more of the following: agreement between the client/owner and contractor, general conditions, supplemental conditions, bid schedule and forms, instructions to bidders, and other items such as supplements to bid forms, agreement forms, bonds and certificates, addenda, and modifications. As with the drawings and specifications, these are legal documents.

Non-technical provisions also include the engineer's construction cost estimate which is "a designer's prediction regarding the probable cost of a construction project"

Because of liability concerns, some design professionals use the expression "opinion of probable cost." This cost estimate, or whatever it is called, should remain confidential until after the bid opening. General conditions define the rights, duties, and responsibilities of three parties defined in lecture 1.

These conditions describe procedures generally accepted in engineering or other technical services. Examples of items typically included under the umbrella of the general conditions are payment and completion procedures, scope change provisions, insurance and bonds, schedule, and means of settling disputes.

Supplemental conditions, which are also called special provisions, are extensions of the general conditions and address site-specific requirements and other idiosyncrasies of a project. Examples include special times when work may proceed, specific insurance and bonding requirements, daily damages for delays, permits that will be needed, hourly wages to be paid, temporary facilities to be provided, and the need for security personnel.

The client, owner, or customer may require that bids be submitted in a specific format or fashion. This leads to the engineer developing bid forms that will be completed by bidders. Similarly, special instructions to bidders may be prepared to explain steps in the bidding process such as how to obtain a set of bidding documents, place and time to submit a proposal, withdrawal of a submitted bid, and conditions under which proposals could be rejected.

3.3 Design as Risky Business

The design process can also be viewed as "risky business". When an individual or an organization undertakes design, they are aware of the possibility, however remote, that a quality design may not result. The resulting structure, facility, system, product, or process may fail to meet all requirements.

Engineers and other technical professionals, as well as other innovators and creators such as writers, composers, painters, and poets, share an apprehension or fear that they won't be able to do the task at hand. Their innovative-creative process is sometimes stymied by "writer's block."

This fear is probably best surmounted by recognizing and acknowledging it, reflecting on one's depth and breadth of understanding of the problem at hand, drawing on one's understanding of science and engineering fundamentals, conferring with colleagues, being open to creative and innovative approaches, and working hard and persistently.

Failure of a structure, facility, system, product, or process can have dire consequences in terms of loss of life or great economic cost.

Because each non-trivial design is new and unique, there cannot be a 100 percent guarantee of success. That which is designed is only as safe as its weakest element. Each design is an untested hypothesis. The test is the structure, facility, system, product, or process itself and how it functions. Failures can, in a cold academic sense, be explained as disproved hypotheses.

The designer strives to reduce the probability of disastrous failure by conducting risk analyses, the designer strives to reduce the probability of disastrous failure by conducting risk analyses, providing redundancies and safety factors; and studying failures.

The Author of "Beyond Failure: Forensic Case Studies for Civil Engineers", Norbert J. Delatte, Jr. (2009) says, "I would like to instill a sense of failure literacy in you. Poets and authors are expected to have intimate familiarity with the work that has gone on before: Shakespeare's sonnets, Hemingway's short stories, and so forth. In the same way, engineers analyzing and designing structures and systems need to know how similar facilities have performed in the past and when and how they failed."

I would recommend the book, ***"To Engineer is Human: The Role of Failure in Successful Design" by Henry Petroski.***

3.4 Design as a Personally-Satisfying and People-Serving Process

More Than Applied Science

Another way to understand and appreciate design is to see it as part of an often creative-innovative process that culminates in a tangible, personally-satisfying, and people-serving result.

To create means to originate, make, or cause to come into existence an entirely new concept, principle, outcome, or object. Similarly, to innovate means to make something new by purposefully combining different existing principles, ideas, and knowledge. Essentially all engineers synthesize, some innovate, and a few create.

Although technical professionals use science in design, design is much more than rote application of science. A designer's work is much like that of the writer, composer, painter, sculptor, and poet in that bits of what is known or has been experienced are re-combined, typically via a trial and error, iterative process, in a unique and new fashion.

Author and engineering professor Henry Petroski (1985) says it this way: "It is the process of design, in which diverse parts of the given-world of the scientist and the made-world of the engineer are reformed and assembled into something the likes of which Nature had not dreamed, that divorces engineering from science and marries it to art."

Engineer and author Samuel Florman (1987) argues that the creativity and innovation necessary and prevalent in the best design can be emotionally fulfilling. The fear of personal failure is more than offset by the deep and lasting satisfaction associated with the design of a structure, facility, system, product, or process that serves the user and society. The possibility of that satisfaction is a magnet that pulls many young people to the study of engineering and other technical fields.

Petroski (1985) reinforces the preceding thoughts about the anxiety and satisfaction found in design by noting that the image of the writer staring at a blank page with a wastebasket full of false starts is analogous to the technical professional starting a design. Likewise, the image of the writer learning of a reader's enjoyment and enlightenment resulting from his or her writing or the image of the painter seeing the enjoyment of people viewing his or her work is very similar to the image of the engineer or other technical professional witnessing the aesthetic impact and effective functioning of his or her creation.

While recognizing the importance of efficiency and economy in design, Billington (1986) asserts that achieving an aesthetic result requires something else and "that something is imagination – a talent for putting things together in unique ways that work, that are beautiful, personal, and permanent."

Creators and innovators derive great personal satisfaction from the fruits of their efforts partly because of the uniqueness of the result. However, engineers and other technical professionals often experience an even higher level of satisfaction because the creative or innovative result is useful to society.

Aspiring to Creativity and Innovation

Each of us has access to the satisfying and productive creativity and innovation inherent in the design process. That creativity and innovation can be accidental. A better option is to practice intentional creativity and innovation using appropriate tools and techniques to stimulate creativity and innovation.

3.5 The Words "Engineer" And "Create"

Not only is creativity, as exemplified by design, one of the principal functions of engineering, the words "create" and "engineer" are closely intertwined linguistically.

Petroski (1985) and Florman (1987) both explore the origins of the word "engineer."

Petroski states that "engineer" originally meant "one (a person) who contrives, designs, or invents." That is, "engineer" was synonymous with creator. This use preceded by a century the idea of an engineer as one who manages an engine.

According to Petroski, the association between engineer and engine began in the mid-1800s with the emergence of the railroad as the metaphor of the industrial revolution. Petroski concludes his exploration of the origins of the word "engineer" by noting that even today there is a "confusion of the contriver and the driver of the vehicle."

Florman traces "engineer" back to the Latin word "ingenium," which meant a clever thought or invention and was applied in about 200 A.D. to a military battering ram. That is, "engineer" was synonymous with that which was created. Later, in medieval times and during the Renaissance, the French, Italian, and Spanish words, respectively, "ingenieur," "ingeniere," and "ingeniero" came into use originally referring to those who designed and built military machines such as catapults and battering rams. In English, the word progressed from the fourth through seventeenth centuries as "engynour," "yngynore," "ingener," "inginer," "enginer," and, finally, "engineer."

Thus, Petroski and Florman agree that "engineer" has deep roots in creativity. Petroski claims that the first emphasis was on the creative person and Florman believes it was on what was created.

However, both agree that “engineer” has its roots in contriving, inventing, designing, and creating. Or, to reiterate the subtitle of this chapter, to engineer is to create.

Closing Thoughts

Design is the essence or root of engineering because this often personally-satisfying and people-serving effort results in useful structures, facilities, systems, products, and processes. These fruits of design meet needs, solve problems, and realize opportunities.

Creating, an essential element of some design, is historically and linguistically linked to engineering. Aspirationally, to engineer is to create.