On Capstone Design: Perceptions, Reflections, and Practices

Waddah Akili
Principal, Geotechnical Engineering, Ames, Iowa, USA
Email:w.akili@isunet.net

Design is undoubtedly the most distinguishing activity of engineering. The general trend today of increasing the design component in engineering curricula is part of an effort to better prepare graduates for engineering practice. Although the presence, role, and perception of design in engineering curriculum have improved markedly in recent years, there is a widespread feeling that the intellectual dimension of design has not received the attention it deserves. The paper begins by addressing design as a "thought" process. Several aspects of "design-related" education, that students of engineering design should be exposed to, are outlined. Finely, the paper identifies common structures of a typical capstone design course and asserts that trying to satisfy the needs of industry in capstone design courses is a central issue.

Introduction

Design is widely considered to be the central and the most distinguishing activity of engineering. The paper argues that design thinking is complex, hard to learn, and hard to teach. What are the thought processes that precede design? What skills should an engineer acquire to become a good designer? It has also long been understood that engineering institutions should graduate engineers who could design effectively to meet social needs. Designers, today, are making products and systems increasingly complex as they work to improve robustness by increasing the number of components and their interdependencies. Further, designers are required to expand the boundaries of their design to include such factors as the environment and social impacts in their designed systems[1]. Such trends suggest that engineering designers need to acquire skills that help them cope with complexity. In response, academic disciplines should also include specific programs that support the design thinking skills that engineering students should experience. The concern here is that the intellectual dimension of "design thinking", that precedes design class work, is missing in todays teaching of design.

The paper sheds light on several dimensions of design-related issues: ***first***; provides some definitions of design and design-related terms; ***second***, focuses on design-related education; and ***third***, identifies the common structure(s) of a capstone design course. What does "design" mean in an engineering context? What are the qualifications of a designer? Can design be taught? If so, who can teach it? These questions will be addressed in the paragraphs that follow.

Definitions plus Relevant Thoughts & Processes

Engineering design as stated by Dym et al. in 2005 is "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" [2] . This definition presents design as a thoughtful process that depends on systematic, intelligent generation of design concepts and the specifications that make it possible to realize these concepts.[2] Sheppard's characterization of what engineers as designers do: "They scope, generate, evaluate, and realize ideas".[3] In the context of engineering design, creativity is important, but it is not design! *Design problems* do reflect the hard fact that the designer has many constraints that may positively or negatively affect the outcome of the design, i.e., the designer has a client to satisfy and for whose benefit the item/artifact and/or project is being developed.[2]

There are many approaches to characterizing *design thinking* and *design processes*. These characterizations, often associated with good designers, would include:

- view design as an inquiry and/or iterative loop of divergent–convergent thinking,
- focus on the "big picture" in all stages by including: systems thinking and systems design,
- handle uncertainties that are likely to arise,
- make decisions,
- think and act as a member of a team,
- think and communicate using design languages.

The starting point of any design project, irrespective of the object or nature of the project, is the *problem definition phase* characterized by asking relevant questions and attempting to find plausible/realistic answers. No sooner has a client or professor defined a series of objectives for a design project than the designer - whether in a consulting office or in a classroom - want to find out what the customer really wants. Questions such as: what is an economic project? How do you define the best design? What is a safe design? What are the factor(s) that will affect the design the most? Phrasing it differently, knowledge resides in the questions that can be asked and the answers that can be provided. [2] A sequence of inquiry characterized by a hierarchy: certain questions need to be asked and answered before other questions can be asked. There is a set procedure which constitutes the inquiry process in an epistemological context. Taxonomies of such a procedure or inquiry process have been extended to computational models [4], to the intricacy between asking and learning [5], and would also apply to the questions students ask during a class and/or tutoring session. [6]

There are two classes of questions within a design context; the first is the category of questions that do have a specific answer, or a specific set of answers. Such questions are characteristic of *convergent thinking*, where the questions attempt to converge on and reveal "facts." As such, answers to converging-type questions are expected to be truthful and verifiable. The second category of questions is diametrically opposite to the first, and is characteristic of *divergent thinking*, where multiple alternative known answers exit, regardless of being true or false. The key distinction between the two types is that *convergent* questions operate in the knowledge domain; whereas *divergent* questions operate in the concept domain[2]**.**This has strong implications for teaching conceptual design thinking, since concepts need not be truthful or have true value, whereas knowledge does indeed!

Design thinking, therefore, is seen as a series of transformations from the *concept domain* to the *knowledge domain*. Such questioning and thinking is the "backbone" of any design process, and the major tool by which designers add to the pool of engineering knowledge.[7] The significance of the transformations between the concept and knowledge domains is further supported by the finding that the combined incidence of deep reasoning questions and generative design is shown to correlate positively with performance in arriving at design solutions[8]**.**Therefore, any properly produced design is preceded by effective inquiry that includes both a *convergent* component (lower level and deep thinking questions) and a *divergent* component (generative design questions intended to create the concepts upon which the design is based).

The forgoing discussion raises questions relevant to teaching design. Clearly, the *divergent* inquiry in design thinking is neither recognized nor included in most engineering curricula. For example, it is not acceptable for a student to respond to a final exam question in an engineering course by providing multiple answers. Students are expected to engage in a convergent process by formulating a set of reasoning questions and work toward the one "unique" answer. In this regard, students ability to converge is being positively assessed when partial credit is given for the "thought process", even if the answer is wrong. The time is right to introduce the iterative *divergent-convergent* process, i.e., to develop better pedagogical approaches to engineering design.

There are several open research questions on design pedagogy that have their roots in *design thinking* and related aspects. For example, how can effective inquiry, the systematic interplay between *divergent and convergent* questions, be taught and made use of in engineering education? The answer is not readily available. But making use of *active learning* methods in the classroom will help in raising students' awareness of the effective inquiry process in design. However, the real challenge is not the adoption of the principles of *divergent–convergent* inquiry; rather it is the integration of *divergent–convergent* inquiry into an existing engineering curriculum. In this context, can exam questions in an engineering course be designed to require students to generate concepts by asking generative design questions followed by reasoning about these questions, before offering solutions? If such exams could be designed, how would their concept generation performance be graded, since concepts are neither true nor false? In a similar vein, how are students to assimilate the idea that design is expressed and applied in multiple languages?

Design thinking and related concepts is evolving, in large part because design has emerged as a recognizable field of research that is supported by national funding agencies such as: the National Science Foundation (NSF). As a consequence, it is expected that better learning models will become available in the near future[2]. Therefore, it is important that design educators stay in close touch with the on going research because the fruits of design-related research enable both better understanding and better articulation of what is involved in design.

Focusing on Some Shortcomings in Design-Related Education

Recently, designers, throughout the world, have helped develop an increasingly complex "built" environment that includes some major large-scale civil engineering projects. Simultaneously, designers have been pushing the envelop at relatively fast rate making products, systems and engineering projects increasingly more complicated as they strive to improve reliability and increase service-life by increasing number of components and their interdependencies. Further, designers have to expand the boundaries to include environmental factors, social impacts, and public safety issues in their designed systems and projects. The trends today suggest that engineering designers are in need of skills and experience to help them cope with the complexity and facilitate the arrival at optimum design. Invariably, this type of: knowledge, skills, and related experience need to find its way to the classroom through curricula updating, proper counselling and mentoring, and insuring a conducive environment. This section focuses on four aspects of design education believed to be of relevance to enabling young designers, and students in particular, to embark on the mission.

1. Thinking about a system's approach: A good designer is some one who can anticipate and deal with intended and unintended consequences resulting from interactions among the multiple factors of the system. Exposure to system analysis and system dynamics – preferably through a rigorous course(s) - would assist the designer in sorting variables, prioritizing, and managing the design process. Unfortunately, these skills are not common, do require prerequisites, and regarded by most as difficult to learn. Many different teaching methods have been proposed to improve people's abilities to grasp and retain knowledge under this category. Recognizing that there are difficulties in proper delivery of systems analysis and systems dynamics to engineering students; the fact remains that these tools are extremely useful for someone who plans to become a designer. Therefore, ways have to be found to enhance the understanding of systems' thinking, in general, and at the same time, to develop educational experiences that could improve learning outcomes.

2. Looking at risk management and uncertainty: Engineering design is carried out relying on incomplete data, imperfect models, often with unclear objectives, and other potential problems and constraints. The effects of such uncertainties on the design of a project may have serious consequences unless proper safeguards have been undertaken based on probabilistic and statistical approaches to design and factors affecting design. Some have argued that current undergraduate curricula greatly underemphasize the theory and application of probability and statistics in engineering. [9] Research has revealed that people are generally prone to serious errors in probabilistic and statistical thinking, including neglect of prior probabilities, insensitivity to sample size, and misconceptions of regression[10]. The formal course work in probability and statistics falls terribly short of exposing engineering students to encountered errors, e.g., systematic underestimation of uncertainty. Engineering educators are concerned, and some have been working to alleviate the difficulties by stressing conceptual understanding, emphasizing active teaching methods, and using more graphics and simulations. [11] There is a long way to go with regard to uncertainty and the way it ought to be handled in the classroom. Suggested improvements and alterations have included the following:[12]

- offer probability and statistics early in the program,
- include "uncertainty" and its implications in engineering analysis courses,
- consider offering technical electives, in this domain, and let "uncertainty" be a central theme,
- make use of modern computational tools to support probabilistic thinking .

Such curriculum changes may fall short of meeting set goals without adequate research aimed at continued improvements in probabilistic and statistical thinking for engineering courses in general and the design component in particular.

3. Estimation: A main challenge of a project design is the number of variables and their interactions during the design process. Often, the system stretches beyond designers' capability to grasp all of the details simultaneously [2] .One strategy for coping with the many variables is to bring the system back within the limits of human mental capacity by focusing selectively on a limited number of factors, preferably the most significant ones. Designers are usually good at estimation. They are able to size up parameters, sort them out in terms of their relative importance, and neglect the ones that have less impact on the project. Today's graduates are not good at estimation [2] .This poor performance by the new graduates appears to be related to a weak conceptual understanding of basic engineering science, limited ability to form appropriate analogies, weakness in visual perception, short-term memory, and insufficient interaction with their physical surroundings. Also, current engineering education emphasizes sophisticated methods for precise calculation; thus may underemphasize approximation skills[13].Attempts to rectify the situation would require research and development and eventually instigating potential changes in curricula and teaching methods.

4. Physical modeling and experimentation: Unfortunately, the advent of the computer and its impact on teaching engineering has made it easy to produce computer-based models at the expense of physical models. This fact is behind a general trend of teaching applied engineering subjects with minimal students' involvement with physical set-ups including laboratory experiments. Carrying out laboratory experiments and generating experimental data, visiting a project site, and using pencil and paper to produce a schematic, are gradually fading away. These traditional tools were instrumental in developing an engineering common sense. It is argued here that generating data from physical models is potentially a great learning tool, particularly when the model is built by the students. Building a model, testing a model, generating physical data from the model, and analyzing said data, help students alternate between *inductive* and *conductive* processes, thus broadening their design vision and understanding the experimental approach to engineering design. There is potentially a real need to research the ways to teach engineering students how to make proper use of physical models and experiments.

The specific aspects (discussed above) of: thinking/implementing a systems approach, looking at risk management and uncertainty, estimation, and physical modeling and experimentation – are intended to pin point some shortcomings in design-related education that need to be addressed using a principled approach to dealing with these difficulties. On the other hand, it seems that expanding courses as noted would raise the cost of education (e.g., involvement of experienced faculty, training young faculty, smaller sections, etc.), but, on a macro scale, these costs are relatively small compared to the lost human talent in the engineering pipeline.

Common Structure of a Capstone Design Course

The general structure of a capstone design course depends largely on the objectives of the course and the level at which the course is implemented. There are several levels at which design courses can be offered: i) the engineering *college level*, ii) the engineering *program level*, or, iii) the engineering *stem level*. A design course at the engineering *college level* may include students from any engineering discipline within the college; a course at the engineering *program level* includes students from one department or discipline in the college; and a course at the engineering *stem level* focuses on one specific area within the particular department or discipline. For example, a design course at the *college level* might involve students from civil engineering and other departments as well. A design course at the *program level* would be restricted to civil engineering students; while a course at a *stem level* would involve civil engineering students with a specific concentration within civil engineering such as: structural, transportation, or environmental engineering. The majority of capstone design courses, however, appear to fall in the engineering *program level* category.

The structure of capstone design courses do vary significantly from one college to another. Also, there are some variations between one department and another. Factors such as department tradition, goals of individual instructors, degree of faculty participation, and availability of resources affect the structure of individual capstone courses. But nearly all have the same basic objective: providing students with experiential learning activities that satisfy set criteria, i.e., in the US, it is ABET Design requirements that need to be met.[14]The ABET requirements must include some of the following: "*development of student creativity, use of open-ended problems, development and use of design methodology, formulation of design problems, alternative solutions, and detailed system description. Further, it is required to include constraints such as economic factors, safety, reliability, ethics, and social impact. Courses that contain engineering design are taught at the upper-division level. Some potion of this requirement must be satisfied by at least one course which is primarily design, preferably at the senior level, and draws upon previous coursework in the relevant discipline"*[14].

A proliferation of capstone design experiences, over the last decade, has taken place at many colleges of engineering – all seem to meet some of the requirements noted above. The ABET requirements is the common thread that links all such experiences for all engineering disciplines, throughout the US, and also in some other countries that have chosen to use ABET's requirements.

Another factor that has influenced the development of capstone design experience has come from the needs of the industrial sector. Capstone design courses have been developed to better prepare students to meet the requirements of industry, by emphasizing design and the practice. To try to satisfy the needs of industry is a central issue of nearly all design courses, and capstone-type design in particular. Industries have often promoted senior-level project courses by providing funding, equipment, and expertise. Also, some do provide awards and incentives to students who excel in their work.

In the US, industrial sponsors, by and large, appoint a liaison engineer to assist students and follow the progress of the project. The involvement of a liaison engineer is a positive step in achieving success. Having students feel responsible and accountable to an industrial "customer" is an important factor in developing self-confidence and interpersonal skills, and learn about the practice. The success of a project can often be assessed by the frequency of interaction between liaison engineers and students[4,13].Opinions vary as to the validity and effectiveness of industry-sponsored projects. Those in favour of industry-sponsored projects insist that students will not know what *real engineering* is like unless they work on a *real world* problem. On the other hand, those opposed to industry-sponsored projects argue that many such projects are not true engineering and often contain low level analyses that do not add anything new to students' knowledge and skills. Industry may also have little sympathy for students' schedules, course loads, and other commitments and restrictions that could interfere with project completion .It may also be hard to find an industry-sponsored project that meets declared project requirements than to make up a tailor-made project that is for a specific course or set of courses. Despite differing views, industry-sponsored projects continue to be a major source of capstone design activities and seem to be increasing in number.

Concluding Remarks

The paper reviews the role of design in engineering curricula, identifies several dimensions of design thinking, looking particularly at divergent-convergent model, sheds light on design–related education issues, describes the common structure of a capstone design course, and identifies those factors that influence the development of the capstone course the most. In breief, available research asserts the need to incorporate those habits of mind, teaching skills, and the tools of design thinking into all parts of the engineering curriculum, particularly in design and design-related courses. There is a clear need to expand the number of faculty members interested in and capable of teaching design, and to create the facilities needed for modern, project–based design courses. Undoubtedly, design education represents serious challenges and great opportunities for all involved. The way to get started, is to provide more forums where design practitioners, design teachers, design researchers and cognitive scientists can come together to collaborate on all of the issues addressed above.

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