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Defining, Teaching, and Assessing Engineering Design Skills

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ABSTRACT

The paper discusses a systematic approach for defining, teaching, and assessing engineering design skills. Although the examples presented in the paper are from the field of aerospace engineering, the principles apply to engineering design in general. What makes the teaching of engineering design particularly challenging is that the necessary skills and attributes are both technical and non-technical and come from the cognitive as well as the affective domains. Each set of skills requires a different approach to teach and assess. Implementing a variety of approaches for a number of years at SJSU has shown that it is just as necessary to teach affective skills, as it is to teach cognitive skills. As one might expect, each set of skills presents its own challenges.

Keywords: *Aerospace, Course Design and Assessment, Engineering Design, Project-Based Learning, Teaching Design*

INTRODUCTION

Design is the heart of engineering practice. In fact, many engineering experts consider design as being synonymous with engineering. Yet engineering schools have come under increasing criticism after World War II because they have overemphasized analytical approaches and engineering science at the expense of hands-on, design skills (Seely, 1999; Petrosky, 2000). As the editor of Machine Design put it, *schools are being charged with not responding to industry needs for hands-on design talent, but instead are grinding out legions of research scientists* (Curry, 1991).

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In response to this criticism and to increase student retention, many engineering schools, including SJSU, introduce design at the freshman level to excite students about engineering. Freshman design also helps students put into perspective the entire curriculum, by viewing each subject as a necessary tool in the design process. Design is also globally dispersed in a variety of junior and senior level courses in the form of mini design projects and is finally experienced in a more realistic setting in a two-semester, senior design capstone experience.

The paper first attempts to provide a comprehensive definition of design skills. Subsequently, it presents a model for curriculum design that addresses these skills. Lastly, it presents ideas for assessing student competence in design. What makes teaching engineering design particularly challenging is that the necessary skills and attributes are technical as well as non-technical, and come from the cognitive as well as the affective domains. For example, the ability to define "real world" problems in practical (engineering) terms, to investigate and evaluate prior solutions, and to develop constraints and criteria for evaluation are technical skills, while the ability to communicate the results of a design, to work in teams, and decide on the best course of action when a decision has ethical implications are non-technical skills. Most technical skills are cognitive, however, there are several skills from the affective domain as well, such as the willingness to spend time reading, gathering information and defining the problem, and the willingness to risk and cope with ambiguity, to welcome change and manage stress. All these skills, technical and non-technical, cognitive and affective are essential for engineers, yet each requires a different approach to teach and assess.

DEFINING ENGINEERING DESIGN SKILLS

What is Engineering?

To define the skills necessary for design engineers we need to start with the definition of engineering itself. Nicolai (1988) defines engineering as *the design of a commodity for the benefit of mankind.* Obviously, the word *design* is key to the definition of engineering. Engineers design things in their attempt to solve everyday problems and improve the quality of our lives. As Theodore Von Karman put it: *A scientist discovers that which exists. An engineer creates that which never was*.

What is Design?

The next step in our search for design skills is to define design itself.

"Design is a process through which one creates and transforms ideas and concepts into a product that satisfies certain requirements and constraints."

Design requirements are usually technical and describe the performance expectations of the product, as specified by the customer or a perceived need. For example, a new passenger airplane may have mission requirements such as:

- A range of 3,000 km (i.e., the distance it will be able to fly without refueling).
- A payload of 100 passengers (i.e., the number of passengers along with their luggage it will be able to carry).
- A flight speed of 750 km/hr at a cruise altitude of 10 km.
- A takeoff field length of 1,500 m at standard sea level conditions.

The performance requirements specified by an airline (the customer), however, are not the only technical requirements that a passenger airplane must meet. To be certified, the plane must also satisfy additional airworthiness requirements. For example, FAR 25.121 part(b), refers to the ability of the plane to climb with one engine inoperative and requires that:

- In the takeoff configuration with the landing gear fully retracted but without ground effect the airplane must be able to maintain a steady climb gradient of at least 2.4% for two-engine airplanes, 2.7% for three-engine airplanes, and 3% for four-engine airplanes at a climb speed that is also specified and known as V2 (Flightsim Aviation Zone, 2010).

Such airworthiness requirements often prove to be more challenging than the original performance requirements specified by the customer. Additional design requirements, not specified by the customer, are not unique to aerospace engineering. For example, civil and architectural engineers must satisfy building code requirements, usually set by cities or countries.

The definition of design also mentions constraints. Constraints are sometimes difficult to distinguish from requirements. They may be viewed as limitations stated in regards to materials, cost, environmental factors, etc. For example, the Hughes H-4 Hercules aircraft, the largest flying boat ever built, was made out of wood because of wartime restrictions on the use of aluminum (Wikipedia, 2011). Another example is the noise standards for transport aircraft (Flightsim Aviation Zone, 2010).

In summary, design engineers must satisfy technical requirements, as specified by the customer and possibly additional technical requirements related to safety. Furthermore they must be concerned with the broader impact of their designs to individuals, the society, and the environment. This has become increasingly more important in our interconnected, globalized world.

Pink (2005) adds yet another challenge to engineering design, one that relates to aesthetics. He argues that because of the 'abundance' of products we have come to expect in the 21st century, the lower manufacturing cost in many countries, and the fact that many engineering tasks can now be automated, *it is no longer enough to create a product that's reasonably priced and adequately functional. It must also be beautiful, unique, and meaningful.* This requirement adds a new dimension to engineering design, a dimension that has much in common with the creative arts.

The Engineering Design Process

The next step in our search for design skills is to look at the engineering design process. Figure 1 is an attempt to illustrate this iterative process, as it takes place in our brain (Nicolai, 1998).

Design begins with brainstorming of ideas. This takes place in the right (creative) part of the brain. There are virtually no rules in generating these ideas. In fact, it is desirable to come up with as many ideas as possible and allow for "wild" ideas as well as conventional ones. While brainstorming, the right brain tends to be holistic, intuitive, and highly nonlinear (i.e., it jumps around). It sees things in their context as well as metaphorically, recognizes patterns, focuses on relationships between the various parts and cares about aesthetics.

Subsequently, each idea is evaluated in the left (analytical) part of the brain under very rigid rules. The left brain acts as a filter on the ideas generated, deciding which ones are viable under the current rules and which ones are not. The left brain tends to be logical, sequential, computer-like. It sees things literally and focuses on categories.

As Figure 1 illustrates, the design process involves an iterative cycling through a sequence that involves creative, imaginative exploration, objective analytical evaluation, and finally making a decision. It is this context, known also as convergent – divergent thinking (Nicolai, 1998), in which one should look for the skills and attributes necessary for a good design engineer.

But there is more to the iterative nature of engineering design than the interchange between the right and the left brain illustrated in Figure 1; iteration is also necessary because of the open-ended nature of design. It is simply not possible to follow a linear, step-by-step process to arrive at a single answer or a unique product that meets our need. First of all, design requires numerous assumptions because there are always so many unknowns. Some of these assumptions may be proven wrong down the road, requiring us to go back, make changes, and repeat our calculations, hence the need for iteration. The non-unique nature of design becomes obvious when one looks at the multitude of products available in the market to address a given need.

Figure 2 illustrates the engineering design process. Engineering design begins with identifying a need. This need is articulated in terms of specific technical requirements that the product must meet. Following this design specification engineers research existing solutions to the problem before proposing any new ones. Brainstorming is the most creative part in

Figure 1. The engineering design process: an iteration between creative synthesis and analytical evaluation (adapted from Nicolai, 1998)

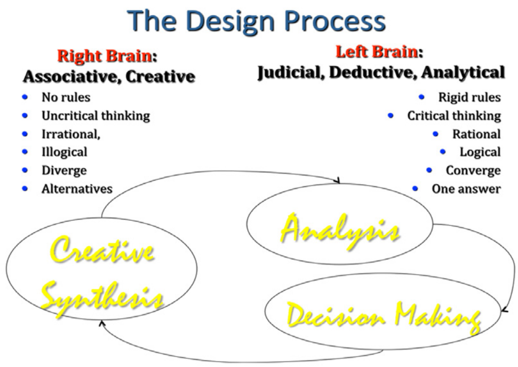
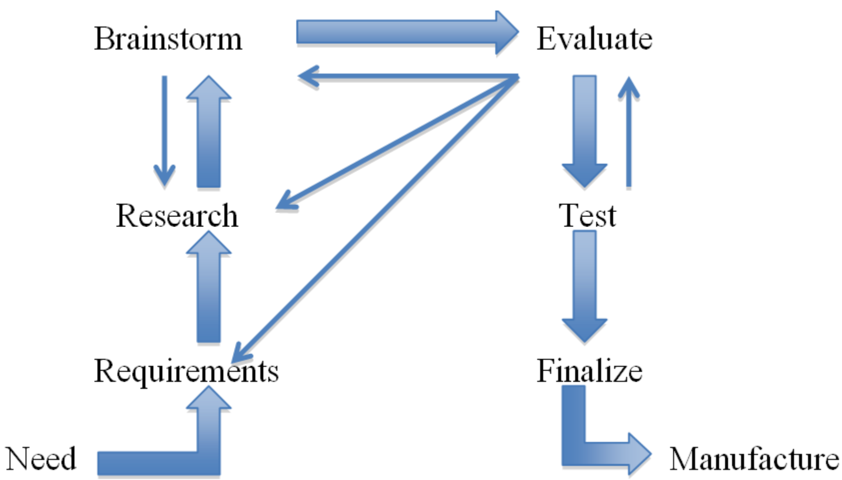


Figure 2. The engineering design process: from identifying a need to production



the design process. The members of the design team who brainstorm typically bring various perspectives and expertise to the problem. The goal is to create as many ideas as possible, including unusual and wild ones. To achieve this goal, participants are not allowed to criticize any ideas put forth. Rather, to create synergy, they are encouraged to build on others' ideas. After brainstorming the group selects two or three of these ideas to move forward with evaluation. Each proposed concept is analyzed systematically using appropriate engineering science in an effort to prove its feasibility and functionality. Hopefully, at least one of these concepts will prove feasible through analysis. A model is then built for actual testing. The tests will hopefully validate one of the proposed concepts, at which point the design is finalized and goes into production.

Design also requires compromise because requirements often conflict with each other. For example, to provide comfort for airplane passengers one needs a large cross-sectional area. But a large cross-sectional area results in greater drag and compromised fuel efficiency, especially at high speeds. A successful aircraft designer must decide where to draw the line between these two conflicting requirements.

Skills and Attributes of Design Engineers

Clearly, engineering design is a very complex process and as such, it requires several, very different from each other, sets of skills. These are briefly discussed in the following sub-sections.

Analytical Skills

The right-hand side of Figure 1 attests to the need for traditional engineering analytical skills: solid fundamentals in mathematics, physical science (e.g., physics, chemistry, etc.), and engineering science (e.g., fluid mechanics, thermodynamics, dynamics, etc.). The need for such skills has been articulated in the desired attributes of a global engineer (The Boeing Company & Rensselaer Polytechnic Institute, 1997), as well as in ABET EC 2000, Outcome 3a (Engineering Accreditation Commission):

"A good grasp of engineering science fundamentals, including: mechanics and dynamics, mathematics (including statistics), physical and life sciences, and information science/ technology

An ability to apply knowledge of mathematics, science, and engineering"

Open-Ended Problem Solving Skills

Design skills build upon open-ended problem solving skills. Outcome 3e of ABET EC 2000 (Engineering Accreditation Commission) highlights the need for such skills when it states that engineering graduates must be able to *identify* and *formulate* engineering problems in addition to being able to solve such problems.

Students who are open-ended problem solvers exhibit the attributes listed below (Woods, 1997). Mourtos, Okamoto, and Rhee (2004) classified these attributes according to the various levels of Bloom's taxonomy of educational objectives in the cognitive and the affective domains (Bloom, 1984; Bloom, Karthwohl, & Massia, 1984):

a. Are willing to spend time reading, gathering information and defining the problem (Affective)
b. Use a process, as well as a variety of tactics and heuristics to tackle problems (Cognitive)
c. Monitor their problem-solving process and reflect upon its effectiveness (Affective and Cognitive)
d. Emphasize accuracy rather than speed (Affective and Cognitive)
e. Write down ideas and create charts / figures, while solving a problem (Affective and Cognitive)
f. Are organized and systematic (Affective)
g. Are flexible (keep options open, can view a situation from different perspectives / points of view) (Affective)
h. Draw on the pertinent subject knowledge and objectively and critically assess the quality, accuracy, and pertinence of that knowledge / data (Cognitive)
i. Are willing to risk and cope with ambiguity, welcoming change and managing stress (Affective)
j. Use an overall approach that emphasizes fundamentals rather than trying to combine various memorized sample solutions (Cognitive)

It is interesting to note that the need for flexibility (attribute g) is also established as a desired attribute for a global engineer in a context much broader than engineering problem solving (The Boeing Company & Rensselaer Polytechnic Institute, 1997):

"Flexibility: the ability and willingness to adapt to rapid and/or major change."

The observation that some of these attributes are associated with the affective domain suggests that engineering design is not all about cognitive skills; it is also about acquiring the right attitudes. Although it is not difficult to illustrate the need for such skills in class, their assessment is more challenging and requires special rubrics. Mourtos (2010) presents an example of a set of rubrics developed to assess open-ended problem solving skills.

A View for Total Engineering

Design engineers must be generalists and acquire a basic understanding of a variety of subjects, from within as well as outside their major – in fact, even from outside of engineering – to develop a view for total engineering. This need has been expressed in three desired attributes for a global engineer (The Boeing Company & Rensselaer Polytechnic Institute, 1997):

- *A good understanding of the design and manufacturing process (i.e., understands engineering and industrial perspective)*
- *A multidisciplinary, systems perspective, along with a product focus*
- *An awareness of the boundaries of one's knowledge, along with an appreciation for other areas of knowledge and their interrelatedness with one's own expertise*

For example, an aircraft designer must have a good understanding of the basic aeronautical engineering disciplines: aerodynamics, propulsion, structures and materials, stability and control, performance, weight and balance. In addition, he/she must develop an understanding of how each part is manufactured and how its design and manufacturing affects the acquisition and operation cost of the airplane.

The example illustrates the multidisciplinary nature of engineering design. Clearly, being an expert in one of the fields involved and inadequate in one or more of the rest, will not work well for a design engineer. Furthermore, engineers must take into consideration a variety of constraints when they design a new product. Some of these constraints are technical; some are non-technical. This expectation is stated in Outcome 3c of ABET EC 2000 (Engineering Accreditation Commission):

"Engineering graduates must have an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability."

The importance of taking into consideration non-technical constraints (e.g., social, political, ethical, safety) is further reinforced in other ABET outcomes as well, where engineering graduates are expected to have:

"3f: an understanding of professional and ethical responsibility.

3h: the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.

3j: a knowledge of contemporary issues"

as well as in two of the desired attributes of a global engineer (A Manifesto for Global Engineering Education, 1997):

- *A basic understanding of the context in which engineering is practiced, including: customer and societal needs and concerns, economics and finance, the environment and its protection, the history of technology and society*
- *High ethical standards (honesty, sense of personal and social responsibility, fairness, etc.)*

In summary, the design engineer must develop an aptitude for systems thinking and maintain sight of the big picture, which is often influenced by technical as well as non-technical factors. Clearly, it is very difficult to quantify a set of specific skills to describe the ideal design engineer. Nevertheless, in an effort to facilitate the teaching and assessment of these design skills, the BSAE Program at SJSU adapted the following set of performance criteria:

Aerospace engineering graduates must be able to:

a. Research, evaluate, and compare aerospace vehicles designed for similar missions.
b. Follow a prescribed process to develop the conceptual / preliminary design of an aerospace vehicle.
c. Develop economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability constraints and ensure that the vehicle they design meets these constraints.
d. Select an appropriate configuration for an aerospace vehicle with a specified mission.
e. Develop and compare alternative configurations for an aerospace vehicle, considering trade-offs and appropriate figures of merit.
f. Apply aerospace engineering principles (ex. aerodynamics, structures, flight mechanics, propulsion, stability and control) to design the various vehicle subsystems.
g. Develop final specifications for an aerospace vehicle.

Ability to Use Design Tools

Freehand Drawing and Visualization

Drawing is the ability to translate a mental image into a visually recognizable form. Eventually any design drawing is rendered as a Computer-Aided Drawing (CAD) with the help of appropriate software. However, CAD is not the best medium when a creative design engineer wants to convey an idea of "how things work" to nontechnical people. Freehand pictorial drawing is most easily and universally understood. Furthermore, a freehand drawing can be a very effective and quick way to communicate ideas in three-dimensions when concepts evolve quickly, as is the case during the early stages of design (e.g., brainstorming), at which point it is not worth investing time and effort in a CAD.

Leonardo da Vinci (1452 – 1519) was one of the earliest engineers who demonstrated mastery in freehand drawing, making it possible for us today to visualize how his inventions worked and appreciate his genius (Figure 3). Freehand drawing is a right-brain activity because it is free of technical symbols and it is closely associated with our ability to visualize things in three dimensions, an indispensable design skill.

Computer-Aided Drawing and Computer-Aided Design

Unlike freehand drawing with its artistic flavor, engineering drawing is a precise discipline based on the principles of orthographic projection. In contrast to freehand drawing, engineering drawing emphasizes accuracy, something that has been greatly enhanced by the use of modern computers and graphic capabilities. Today a CAD is much more than a computer generated engineering drawing; it involves an extensive database detailing the attributes of an object and allows it to be rotated, sectioned, and viewed from any angle. This capability is indispensable in the design of complex engineering equipment, such as an airplane, because engineers can now superposition the various subsystems and immediately see potential conflicts. CAD has led to Computer-Aided Manufacturing (CAM), where the machines that manufacture the various components receive their operating instructions directly from the database in the computer.

Kinematics

A design engineer needs skills in kinematics since the various parts of an engineering product move, rotate and may also expand / retract or fold. An understanding of kinematics (e.g., selecting the proper mechanism and visualizing its operation) allows the design engineer to evaluate what will work and what will not work. For example, in the design of an airplane landing gear, the designer must be able to visualize how the gear will fold and retract in its proper space and make sure that it will not conflict with other components in the process.

The skills described in this section fall under Outcome 3k of ABET EC 2000, which states that *engineering graduates must have an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.*

Interpersonal, Communication, and Team Skills

Interpersonal and Team Skills

Archimedes designed his screw pump (Wikipedia, 2007) alone. This was not uncommon in the ancient world. Similarly, Leonardo da Vinci designed his engineering devices, such as the one shown in Figure 3, alone. Today, working alone to design an engineering product is, for the most part, a thing of the past unless, of course, the product is a very simple one. The complexity of modern engineering products requires engineers to work in teams; in fact, sometimes several teams must work together. For example, in the design of a new transport, it is typical to have a team of engineers for each of the disciplines mentioned above (aerodynamics, controls, manufacturing, etc.). These teams work closely together to meet the same set of mission and airworthiness requirements, while at the same time making sure there are no conflicts between the various airplane sub-systems.

Hence, although earlier we expressed the need for design engineers to be generalists, so they can appreciate the multidisciplinary requirements that come into play in the design of a new product, it is not possible for an individual to have enough expertise in each and every one of the technical areas to adequately perform the detail design of all the subsystems, not to mention the analysis of the impact of a new product in a global, economic, environmental, and societal context.

Outcome 3d of ABET EC 2000 states that *engineering graduates must have an ability to function on multidisciplinary teams*. In today's multicultural world, this outcome also implies an ability to collaborate with people from different cultures, abilities, and backgrounds. This is further elaborated in the following four desired attributes for a global engineer (The Boeing Company & Rensselaer Polytechnic Institute, 1997):

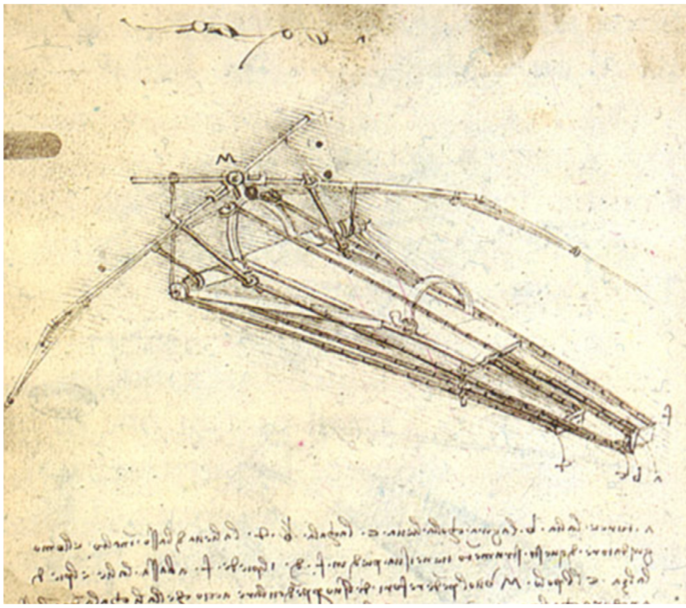
- *An awareness of and strong appreciation for other cultures and their diversity, their distinctiveness, and their inherent value.*
- *A strong commitment to team work, including extensive experience with and understanding of team dynamics.*
- *An ability to think both critically and creatively, in both independent and cooperative modes.*
- *An ability to impart knowledge to others.*

The following performance criteria have been chosen to assess this outcome in the BSAE Program at SJSU:

Students working in teams are expected to:

- Be committed to the team and the project; be dependable, faithful, and reliable. Attend all meetings, arrive on time or early, and come prepared and ready to work.
- Exhibit leadership by taking initiative, making suggestions, providing focus. Be creative, bring energy and excitement to the team, and have a "can do" attitude; spark creativity in others.
- Gladly accept responsibility for work and get it done; exhibit a spirit of excellence.
- Demonstrate abilities the team needs and make the most of these abilities by giving fully to the team.
- Communicate clearly with team members when speaking and writing. Understand the direction of the team.
- Bring a positive attitude to the team, encourage others, seek consensus, and bring out the best in others.

Figure 3. Design for flying by Leonardo da Vinci (the drawings of Leonardo da Vinci)



Communication Skills

Design requires clear and effective communication not only between team members, but also between the team and third parties (management, customers, etc.). Communication usually takes two forms, oral and written and can be informal, such as between team members or formal, such as when the team presents information to third parties. All four types are crucial for the success of a project. Needless to say, good verbal communication requires not only ability to express one's ideas clearly but also the ability to listen carefully and understand ideas and concerns expressed by others. The need to communicate effectively is outlined in Outcome 3g of ABET EC 2000. In the BSAE Program at SJSU the following performance criteria were selected to express the skills embedded in this outcome:

Ability to:

a. Produce well-organized reports, following guidelines.
b. Use clear, correct language and terminology while describing experiments, projects or solutions to engineering problems.
c. Describe accurately in a few paragraphs a project / experiment performed, the procedure used, and the most important results (abstracts, summaries).
d. Use appropriate graphs and tables following published engineering standards to present results.

It is interesting to note that the desired attribute for a global engineer relating to communication skills, includes *listening* but also *graphic* skills as part of the list (The Boeing Company & Rensselaer Polytechnic Institute, 1997):

"Good communication skills, including written, verbal, graphic, and listening."

Although graphic skills were discussed earlier in the topic of freehand drawing and CAD, the term graphic here includes the ability to prepare engineering graphs that illustrate for example, parametric studies pertinent to a particular design. One thing that becomes obvious in this discussion is that the skills and attributes necessary for competent engineering design are so integrated that in some cases it is not even possible to draw clear distinctive lines between them.

CURRICULUM AND COURSE DESIGN FOR TEACHING ENGINEERING DESIGN SKILLS

Like any set of skills, design skills must be introduced early in the curriculum, practiced often, and culminate in a realistic design experience if students are to achieve the level of mastery prescribed in ABET EC 2000 and expected in industry. The following subsections describe how design skills are introduced at the freshman level, dispersed throughout the BSAE curriculum, and culminate in a senior design capstone sequence. The Project-Based Learning (PBL) pedagogical model is used in all the courses where design is taught and students work in teams for all design projects. Non-traditional ways of assessing design skills are also discussed.

First-Year Design

At SJSU engineering design is first taught in our Introduction to Engineering course (E10). E10 is a one-semester, two-hour lecture/three-hour laboratory course for freshmen, required by all engineering majors. Engineering design is taught through hands-on projects (PBL) as well as through case studies in engineering failures, which also bring up the subject of engineering ethics. For each project, students work in teams to research, brainstorm, design, build, test, and finally demonstrate a device in class (Mourtos & Furman, 2002). Typically, students participate in two or three projects during the semester. This course design followed well-established research, which shows that first-year design courses help attract and retain engineering students (Ercolano, 1996).

E10 students report significant gains in their understanding of design and ethics, design report writing and briefing skills (Mourtos & Furman, 2002). They report slightly lower gains in open-ended problem solving skills, including estimation and mathematical modeling. On the other hand, they report low gains in team skills. This was due to the fact that team skills were not taught explicitly at the time of the assessment. Despite a significant amount of time spent working in teams, students needed more guidance and coaching on skills like conflict resolution, task delegation, decision making, etc. These skills are now taught more explicitly.

In addition to student self-reporting, authentic assessment data from course instructors show that engineering freshmen perform fairly well in their design assignments.

Design Globally Dispersed-Teaching and Assessment of Open-Ended Problem Solving Skills

In the BSAE Program design is dispersed throughout the curriculum, so students have an opportunity to practice design in a variety of subjects. Student design practice begins with open-ended problems to help them develop the related skills and attributes described earlier. For example, to help students develop:

a. A habit of doing research before attempting to solve a problem: an extensive literature review is required for all open-ended problems and design projects.
b. Competency in the use of a process, as well as specific tactics and heuristics to solve a problem: a problem-solving methodology is taught and required to use in the solution of all open-ended problems.
c. An ability to monitor their progress following a problem-solving process: students write a reflection on the effectiveness of their problem-solving process and identify their strengths and weaknesses.
d. A value system in which accuracy is more important than speed: students are given

sufficient time to tackle problems, whether in class (exams) or outside of class, and their grading depends heavily on the accuracy of their calculations.

e. A habit of writing down ideas and creating sketches, charts, and figures while solving a problem: students are graded not only on their final answer but also on how well they integrate such features in their solution of problems.
f. An organized and systematic way of approaching problems: students are expected to document in their solutions every step of the problem-solving methodology they are required to follow.
g. An open mindedness and flexibility when solving problems: students are required to consider, analyze, discuss, and present multiple approaches and solutions to a problem.
h. A risk-taking attitude when solving problems: innovative approaches are encouraged; students are not penalized for presenting such solutions, even when the final outcome is not the best.
i. An ability to use an overall approach that emphasizes fundamentals rather than combining memorized solutions as well as an ability to cope with ambiguity and manage the stress: open-ended problems are practiced in all upper division courses.

Design was originally introduced through projects in several junior level aerospace engineering courses. For example, in aerodynamics (AE162), students designed an airfoil for an ultralight aircraft and a wing for a high subsonic transport, both of which had to meet very specific requirements. Similarly, in propulsion (AE167) students designed a compressor and a turbine and they subsequently matched them for placement in a jet engine with specific thrust requirements.

In an effort to address the compartmentalization of traditional engineering curricula this approach was modified in 2005. In each of the junior fall and spring semesters, students now define their own design project that involves applications from at least two courses, taken concurrently in the particular semester (Mourtos, Papadopoulos, & Agrawal, 2006). For example, one project involved the design of a ramjet inlet and required integration of compressible flow (AE164) and propulsion principles (AE167). Another, more ambitious project involved the design of a flexible wing for high maneuverability and required integration of principles from aerospace structures (AE114), aerodynamics (AE162), flight mechanics (AE165), and computational fluid dynamics (AE169).

This project-based integration of the curriculum offers students an opportunity to appreciate the integrative nature of aerospace engineering design on a smaller scale, before they delve into a much more demanding senior design experience.

Senior Design Capstone Experience

In their senior year, aerospace engineering students may specialize in aircraft (AE171A&B) or spacecraft (AE172A&B) design. Both course sequences involve the conceptual and preliminary design of an aerospace vehicle. Depending on the project, the experience may also include the detail design and manufacturing of the vehicle. Although only one of these course sequences is required, a few students choose to take both in lieu of technical electives.

Teaching and Assessment of Team Skills

As anyone who has ever worked in a team knows, team skills are not acquired automatically simply by working in a team; they need to be taught explicitly, practiced regularly, and assessed periodically, just like any other set of skills. Although team skills are now taught in E10 and assessed in every course that involves a team project or experiment, it is in the senior design course sequence that these skills are formally taught and assessed. As the course meets once a week for two and a half hours, the first 15 to 30 minutes are dedicated to building an understanding of how effective teams work. At the beginning of the year, after teams are formed, students engage in various team-building activities. Lessons from these activities are discussed in class. Subsequently, in each class meeting students present and discuss one of the 17 laws of teamwork (Maxwell, 2001). Finally, at the end of each semester students submit a team member report card, in which they evaluate the performance of their teammates as well as their own, using the performance criteria for effective teamwork defined earlier and which are shown also in Table 1. These peer reviews are taken into consideration when assigning individual course grades.

Assessment of Total Engineering Skills

Many student teams choose to participate in the SAE (Society for Automotive Engineering) Aero-Design or the AIAA (American Institute for Aeronautics and Astronautics) Design/Build/Fly competitions. In addition to the conceptual and preliminary design, these teams carry out the detail design of their airplane, which they proceed to build and test. Clearly, these competitions give students an opportunity to go beyond a design on paper and experience challenges related to manufacturability and cost. Often engineering professionals from the aerospace industry mentor students in their designs. Participation in design competitions offers unique learning experiences through interactions with students, faculty, and engineers from educational institutions and companies around the country (US) and the world. Both the SAE and the AIAA competitions attract student teams from universities around the world. Furthermore, it provides unique opportunities for authentic assessment of student design skills by engineering professionals. In addition to the engagement factor, which in itself enhances the students' learning experience in engineering design (Mourtos, 2003), the flight competition itself provides the ultimate test for their designs.

Assessment of Technical Communication Skills

Although students must pass a technical writing course (E100W) and have several design and lab reports evaluated in previous courses, it is again the senior design capstone experience that offers opportunities for more realistic assessment of technical communication skills. For example, students who participate in design competitions have their design reports and drawings evaluated by a team of professional engineers, from whom they receive a score sheet and written feedback. Teams also present their design orally and receive a separate evaluation of their presentation. This kind of feedback naturally adds to any comments given by the course instructor throughout the year. In fact, in many cases it carries a greater weight.

In addition to participating in design competitions, students are encouraged to submit and present papers to conferences (e.g., Johnson et al., 2009; Casas et al., 2008). Whether a student conference or a professional conference, participation provides similar benefits in terms of evaluating student written and oral communication skills.

Safety, Ethics, and Liability Issues

Safety, ethics, and liability issues are addressed in the course through aerospace case studies involving accidents. Students research background information for each case, make a class presentation, and argue about the various issues in class. A written report is also required. Students in general engage in these discussions and perform fairly well in their written assignments not only because safety, ethics, and liability provide an interesting dimension to aerospace vehicle design but also because these assignments are the only ones addressing ABET Outcome 3f in the BSAE Curriculum, and as such, they have been designated as "gateway" assignments. Hence, students must receive a score of 70% or better in these assignments to pass the course, regardless of their performance in the technical aspects of their design.

Economic, Environmental, Societal, and Global Impact

Students discuss in one of their reports the impact of their designs in an economic, environmental, societal, and global context. For example, a team that designed a solar-powered UAV performed a simple analysis on the environmental impact of their airplane by estimating the emissions from a small internal combustion engine with comparable power. They also discussed operating cost taking into consideration the replacement cost of their expensive solar panels every time their UAV crashed. On the other hand, it is not always possible to find interesting and realistic social, political and other types of constraints for all airplanes that students choose to design. Nevertheless, it is important that students develop at least a basic understanding of such issues as well as ways to properly research them before attempting to address them.

To develop such an understanding of these issues as they relate to aircraft design, students perform an additional individual assignment by selecting and researching a topic of interest to them. For example, two very interesting topics selected by students were the impact of airplanes on cultural integration and the contribution of jet aircraft contrails on global warming. Students are required to find at least five references related to their topic, at least two of which must be technical journal articles, conference papers or technical reports. For the rest of their references students may use newspaper or magazine articles and the worldwide web. Students study these references and prepare a two-page paper summarizing the key points of their research and a ten-minute presentation for our class. In their presentation students must include two key questions related to their issue, as a way to facilitate class discussion.

Graphic Communication Skills

To introduce students to freehand drawing a collaboration has been established with the SJSU School of Art and Design. A team of students from the graduate class Artists Teaching Art Seminar (Art 276) visits the aircraft design class to offer a three-hour workshop on freehand drawing, which includes contour drawing, gesture drawing, and perspective. Both groups of students have been very positive about their experience; the art students because they are given an opportunity to practice their teaching skills in a realistic setting; the aircraft design students because they get an opportunity to express themselves creatively within the context of a very demanding engineering course. An example of a free-hand drawing illustrating a

Figure 4. Example of a free-hand drawing in the early design stages

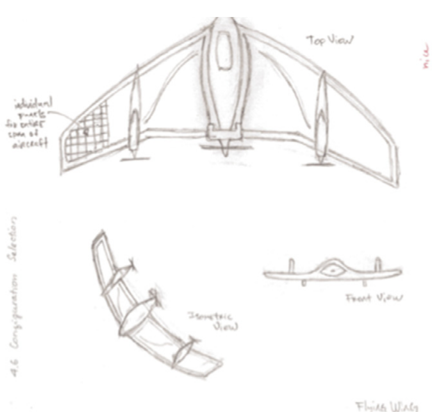


Table 1. Team member report card

Project Title:					
	Criteria	Filled out by:			
		Member 2	Member 3	Member 4	Self
1	*Quality of Technical Work:* Work is correct, clear, complete, and relevant to the problem. Equations, graphs, and notes are clear and intelligible.				
2	*Commitment to Team / Project:* Attends all meetings. Arrives on time or early. Prepared. Ready to work. Dependable, faithful, reliable.				
3	*Leadership:* Takes initiative, makes suggestions, provides focus. Creative. Brings energy and excitement to the team. Has a "can do" attitude. Sparks creativity in others.				
4	*Responsibility:* Gladly accepts work and gets it done. Spirit of excellence.				
5	Has abilities the team needs. Makes the most of these abilities. Gives fully, doesn't hold back.				
6	Communication: Communicates clearly when he/she speaks and when she/he writes. Understands the team's direction.				
7	*Personality:* Positive attitude, encourages others, seeks consensus. Brings out the best in others.				
	Average score				

Grading scale:

5 – Always, 4 – Most of the time, 3 – Sometimes, 2 – Rarely, 1 – Never

Keep in mind that if you award high scores to everyone, regardless of their contribution, team members who have worked unduly hard or provided extraordinary leadership will go unrecognized, as will those at the other end of the scale who need your corrective feedback.

Please write below and on the back of this form one (**minimum**) or more paragraphs about the work of **each member** of your team, including your own. These narratives should amplify the ratings you gave in the table, by (a) identifying the strengths and weaknesses of each individual and (b) suggesting ways in which his / her work can be more effective. Also, evaluate the team as a whole. Feel free to attach additional pages.

possible configuration for a small solar-powered UAV is shown in Figure 4.

Engineering students tend to be very capable with computer programs, including those used in design. For example, a student produced an artist's concept of his proposed very large, luxury airship, as a way of helping his audience visualize the level of comfort and luxury afforded in this kind of vehicle and provide a contrast with the interior one finds in most airlines today (Figure 5).

Naturally, three-view CAD drawings are expected from students in all final design reports. Students are introduced to CAD early in their curriculum with a required freshman-level course in Design & Graphics (ME20). In addition, Computer Aided Design (ME165) is a popular technical elective for many students.

REQUIRED SKILLS FOR FACULTY WHO TEACH ENGINEERING DESIGN

An additional challenge in teaching design is the competence level, as far as design skills are concerned, of the faculty who teach design courses. To provide a thorough analysis of this issue is beyond the scope of this article, however, it is worth mentioning two very distinct reasons, which contribute to this challenge:

Figure 5. Example of an artist's concept drawing for the interior of a very large, luxury airship

a. A successful completion of a Ph.D. degree, required for a faculty position at most engineering schools, entails primarily development of analytical (left brain), research skills. On the other hand, as we have seen, design requires both analytical and creative skills.
b. To earn tenure and promotion in an academic setting engineering faculty are required to perform research, publish in refereed journals, and seek external funding. To maximize their chances for success under this kind of pressure, engineering faculty continue the same line of research they did in graduate school. After all, the venues available for publishing design work or seeking funding to do such work are limited compared with traditional areas of engineering research.

Hence, faculty members who are asked to teach a design course, often find themselves unprepared. One way to address this deficiency is to require engineering faculty to undergo some training in engineering design before teaching a design course. There are many workshops on design for faculty members as well as for engineers who work in industry, sponsored by professional societies, universities, and engineering companies. Professional societies also offer summer fellowships for engineering faculty willing to spend a summer in industry working alongside design engineers. Another way to address this issue is to hire adjunct faculty with current design experience from industry to teach design courses. This solution, however, poses its own problems.

a. While some engineering schools are strategically located in areas where adjunct faculty with design experience are available, not every engineering school is blessed with proximity to engineering companies that may provide such faculty. This issue can be addressed in creative ways. For example, to accommodate an adjunct faculty member who teaches a design course at SJSU, a blended course has been scheduled: traditional (face-to-face) and online. The instructor flies from another state every other week and spends three hours with the students. In between, the course is conducted online using appropriate software.
b. Teaching any subject including design requires not only expertise in the subject matter but also appropriate pedagogical knowledge (Mourtos, 2007). Unfortunately, most engineering faculty do not possess such knowledge, as it is not a requirement

in their job description. This is true for full-time as well as part-time faculty. Our experience at SJSU has shown that both full-time and adjunct faculty have opportunities to develop pedagogical knowledge through experience and reflection by teaching a variety of courses over time as well as through optional pedagogical training available at most universities. As a result, some – certainly not all – of the faculty do develop appropriate pedagogical content knowledge over time and become effective teachers.

CONCLUSION

An attempt has been made to provide a comprehensive list of skills, technical and non-technical, for design engineers. These skills include analytical, open-ended problem solving, a view for total engineering, interpersonal and team skills, communication skills, as well as fluency with modern tools and techniques used in engineering design. In addition to these skills, design engineers must develop certain attributes, such as curiosity to learn new things and explore new ideas, self-confidence in making design decisions, taking risks by trying new concepts, thinking out-of-the-box, and persistence to keep trying when things don't work.

The paper presented course and curriculum design from the BSAE Program at SJSU that addresses these skills and attributes and touched briefly on the challenge of engineering faculty competence in design skills and pedagogy. Some of the elements in this curriculum were introduced several years ago, have been assessed extensively and indicate that students indeed acquire an adequate level of competence in some of these skills. Some of these elements, such as the teaching of freehand drawing through the collaboration with the College of Arts and Design, were introduced only recently and have not yet been assessed. In any case, the attributes of a design engineer, as described above, are difficult to measure and will require the development of special rubrics.

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