The Methods and The Foundation

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A Basis for Engineering Design

The Colorado School of Mines (CSM) surveyed alumni, industry, and engineering students in both 1978 and 1992 about the future engineering graduate. These surveys cited three major attributes that future graduates needed: technical literacy, verbal and written communication skills, and design experience. Curriculum reform in engineering education is underway that stresses the importance of teamwork, an awareness of both society's social and economic concerns, and an ability to adapt to the changing demands of the next century[1, 2, 3]. Many schools have adapted their curriculum to include engineering design courses that focus upon the development of these important skills and that include industrial partners in the curriculum design effort [4, 5, 6]. Aaron Collins[7] received a grant from the National Science Foundation to instrument a laboratory for a four-year design sequence at Mercer University. Their curricula served as an example of the organizational advantages of a four-year sequence by developing process skills as students developed their technical skills. This sequence used data collection and processing as a basis for enhancing students' engineering design skills. The School of Civil Engineering and Environmental Science (CEES) at the University of Oklahoma[8] proposed curriculum changes that would incorporate a single design project integrated throughout the curriculum. This common design project would bring the curriculum together and integrate material learned in early courses. A primary goal of the project is to produce graduates who are self-disciplined, responsible, computer literate, and who can communicate effectively with fellow engineers, management, and the public.

Examination of the literature concerning engineering design provides diverse views of what engineering design is. For example, the Engineer's Council for Professional Development described design in terms of the *processes* that are required to optimally "meet a stated objective" whereas Douglas[9] has described design as a *creative* activity that converts ideas into "processes for producing new materials." Pahl and Beitz[10] consider the integration of technical, systematic, psychological, and organizational aspects of engineering design as "prerequisites for the physical realization of solution ideas." Still others have argued that design includes teamwork and management skills[11, 12.] Based on these different views of engineering design, Bieniawski[13] has argued that design is not typically learned in a classroom setting, but rather through practice.

CSM responded to issues of engineering design and the Future Graduate Profile through development of the Design Stem. The stem consists of four courses: first-year Design (EPICS) [Engineering Practices Introductory Course Sequence], second-year Design (EPICS), Field Session (junior year) and Senior Capstone design. An important component of each of these courses is the contribution of industrial partners who provide teams with authentic engineering projects.

The Design Stem

Engineering companies today assume responsibility for cradle-to-grave engineering of their projects. The life cycle for an engineering design project, schematically represented in Figure 1, begins with the conceptualization stage and quickly progresses to an assessment of resources (Resource and Site Characterization, Technology Assessment, and Economic Evaluation). As management continues to see a potential, the engineers conduct the feasibility design studies to support advancement of the project. As the project approaches the construction phase, engineers ultimately optimize the system. At each stage, the evaluation and analysis requires greater accuracy as well as effort to produce the evidence necessary to continue the process. The type of engineering shifts to trouble-shooting during the construction and operations stages. Finally the team needs to follow up with the reclamation projects necessary to return the environment to its natural state.

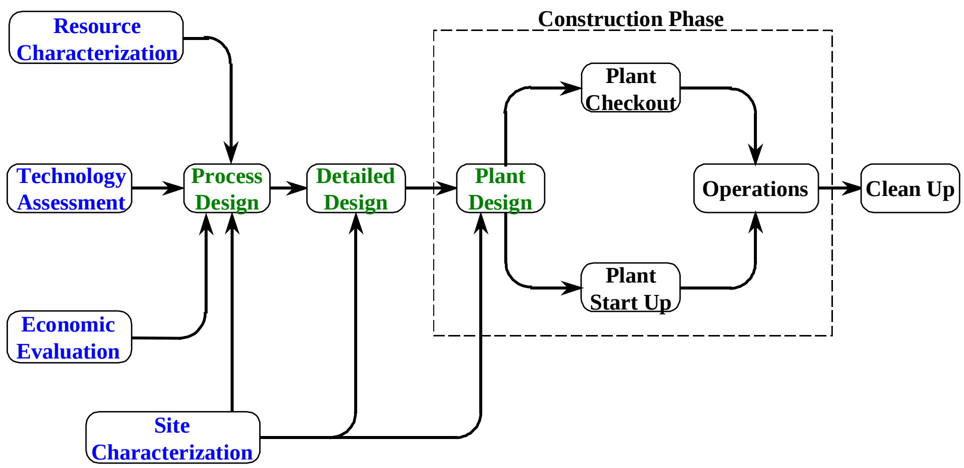

***Figure 1**: Schematic Representation of an Engineering Project Life Cycle*

In this presentation, I propose that this model, central to the process industry, applies equally well and serves as a foundation for an engineering design curriculum. We describe engineering design as a complex, interactive, and creative decision-making process that evolves as the design team synthesizes information, skills, and values to solve open-ended problems. The Design Stem at CSM encompasses a four-year program in engineering design studies, summarized in Figure 2. The Design (EPICS) program oversees implementation of the first two years, although the various disciplines are encouraged to take an active role in the design and presentation of Design (EPICS) II. The disciplines are responsible for years three and four.

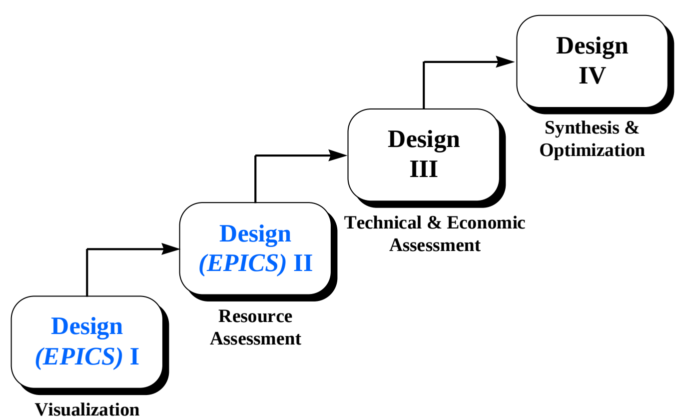

***Figure 2:** Overview of Design Stem Sequence*

Since successful engineering design relies on knowledge, experience and intuition, the instructional method used throughout the Design Stem is a sequence of courses that engages teams in an authentic design process under the mentoring of experienced teachers, employers or colleagues. The process provides a project situation in which teams make decisions, often iterative, to create a system, process, or component to meet client or market needs. The experience passes on to students an engineering lore underlying the method and procedures that characterize professional engineering design. The project enhances creativity that comes from allowing teams to solve problems and to think about the consequence of their decisions. The project also supports critical analysis based on fundamental engineering knowledge and an awareness (breadth) of socio-economic and societal factors.

The Project

The centerpiece of each design sequence, therefore, is an open-ended problem that students work in teams to solve. To help students become skilled at this process, mentors have students learn through practice. Although the mentor's primary role is to apprentice students through their difficulties, mentors also furnish students with instruction or information in carefully selected topics. "Hands-on" application of engineering practice skills facilitates students' learning.

Let us walk through the initial engineering design life cycle stages as a student might experience the Design Stem at CSM. I will first review the purpose and major activities of the first four stages of the design project. I will use an authentic and exciting project we initiated in 1997 to illustrate how the Design Stem models the engineering stages. The project continues to move forward today with hopes that we will move into the construction stage fairly soon. My intent will be to show how the project-based curriculum (the method) creates a learning environment based on a solid foundation, the Design Stem, that models the engineering design life cycle.

Conceptual Design

During the conceptual stage, ideas evolve from the mind of the designer. To communicate these ideas, the engineer relies on graphical skills to portray and develop the design concept. If the team can sell management on the potential, using a limited investment of effort, the project moves to the next stage.

> " In order to produce a new machine, structure or other technological artifact, two separate but closely related processes are generally required. In the first, engineering designers convert the visions in their minds to drawings and specifications. In doing so, they solve an ill-defined problem that has no single 'right' answer but has many better or worse solutions. ... The second process revolves around the finished drawings and specifications."
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> Author Unknown

In the fall of 1997, teams of first-year students at CSM designed interactive playground equipment for children with disabilities. Proposed by Ms. Barbara Melinkovich for the Marshdale Elementary School, the purpose of this equipment focused on having children facing each other. Fourteen pieces of playground equipment were selected from 70 creative designs for further analysis. Although these first-year students of engineering did not possess the technical skills to analyze the equipment, they possessed the creative skills to conceive many very creative designs. Through the first-year curriculum, they learned to communicate these concepts through graphical portfolios – a predecessor to blue prints used for construction.

Resource Assessment

With the concept in mind, the engineers gather information to assess the resources necessary to make the concept a reality. Their efforts focus on the technology, resource, site, and economics critical to the project's success. Sufficient information must be documented about these factors to warrant further expenditure of effort. If the project continues to show promise, management invests resources to move on to the next stage.

Our second-year students explored the resources to make the playground equipment a reality. They gathered technical information from equipment vendors, identifying the standards that dictate product quality. The standards pushed them to explore other regulatory issues and agencies responsible for playground equipment. In order to be competitive in the market place they determined price ranges for playground equipment. Their interactions with vendors, regulatory agencies, and inspectors identified the specifications (codes and standards) that constrain their designs. Through the second-year curriculum, they learn to gather information and identify the specifications that determine performance of their design.

Feasibility Studies

The engineering team assesses the technical and economic feasibility of their design as they compete for valuable company resources. At this stage, they conduct the more detailed technical analysis to confirm the credibility, safety, and reliability of their design. Confident that the design meets the performance criteria, the team analyzes the economic feasibility to confirm that the benefits outweigh the costs. These studies increase management's belief that the design is feasible and worthy of the increased effort to continue the process.

Mechanical engineering students in the first phase of their capstone design course implemented the engineering studies to establish the feasibility of the best three pieces of equipment selected by Ms. Melinkovich. The technical studies focused on structural analysis, which lead to modifications strengthening the equipment for use on the playground. Each team modified the equipment as necessary to create a technical feasible solution. One team, however, failed to recognize the specifications of the client and minimized the potential for interaction between children. They eventually chose to pursue the project through other market places. One team failed to recognize site specifications and requirements of the maintenance department of the school district. They chose to ignore the specifications and their product was rejected by the school district. The final team failed to fully understand the detail of the safety codes. They, however, received approval to proceed provided they made modifications necessary to meet safety codes for the equipment. In each case the teams established the technical feasibility of their product but failed to satisfy non-technical issues, which also determined the feasibility of the product. Through the third-year curriculum, they learned to conduct the detailed engineering studies to confirm the feasibility of their product but also become aware of the non-technical issues, which may impact the team's ability to continue the project.

Detailed (Optimization) Studies

The engineering team now has the commitment to optimize the product quality prior to assembly. This final stage of engineering focuses on modification to improve the performance and to reduce the costs. The team models the design based on insights they gained from the feasibility studies. They explore "what if" scenarios to assess the impact of changes and variables on their design. Ultimately they select the most desirable set of specifications for their design. Based on this optimal solution, management agrees to invest the resources necessary to bring the design to market.

The one remaining team returned to the design board during the second phase of their capstone design course. Their effort focused on refining their design to eliminate trouble spots. In the process, they used their structural models and creativity to create a better piece of playground equipment. In the process of meeting the safety codes, they produced a product that was structurally stronger than their initial design. The result was a piece of equipment that also cost less than originally projected. Through their fourth-year curriculum, they learned to reengineer their product to maximize performance and in the process reduced costs.

Conclusion

I submit to you the advantages that a four-year engineering design curriculum offers the engineering student. The Design Stem not only reinforces technical skills that engineering students develop through their content curriculum but also builds an understanding and confidence in the engineering design process. This learning takes place throughout their educational career in a sequence that follows their technical learning as well as models the engineering design stages of a project life cycle. The project-based curriculum serves as an excellent method if built around the foundation of a four-year design stem. This foundation models the engineering cycle these engineers will experience throughout their technical careers.

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Robert Knecht's 25 years of experience in the industry focused on technical and management support for minerals, energy and waste projects. In addition, he supervised management support for contracts which responded to DOE Cost and Schedule requirements. He directs an engineering design program based on a curriculum that incorporates projects from industry with commercially available, computer-aided design software. His projects require students to implement a design methodology in teams to resolve open-ended problems and to communicate both in written and verbal forms the results of their work.