A Promising Model for Integrating Design in Undergraduate Engineering Curriculum

Bijan Sepahpour and Norman L. Asper
The College of New Jersey

ABSTRACT

A model for incorporation of a comprehensive design experience into a typical four-year undergraduate engineering curriculum is proposed. This model will provide an evolutionary process through which the students would gain the necessary know-how and a high level of confidence for challenging real world problems. The model has been utilized for the past five years at the College of New Jersey. The success rate of this approach is measured by the performance and creativity level of the two generations of students/graduates who experienced the new environment with both the students/graduates of prior years and students/graduates of other institutions. The foundation of the proposed model is laid in the first semester of the freshman year by introduction of a formal course in fundamentals of engineering design and reinforced in the second semester by a course that brings the elements of liberal arts and humanities into perspective. In the remaining three years of the curriculum, design projects and exercises are strategically incorporated all through the engineering courses - targeting the full spectrum of design parameters. Included in these parameters are "Safety, Manufacturability, Cost Effectiveness, Ergonomics, Analytical and Numerical Optimization, use of Commercial Software, Social, Economic and Environmental Factors, Group Dynamics, Project Management and Global Competition." In the senior year, the required 2-semester Senior Design Project will challenge the students to fully implement the culminating experience they have gained through the above process.

I - INTRODUCTION

Engineering education is constantly evolving to meet the changing needs of students. As one would expect, many of these changes are initiated and paced by the radical advances in technology. In addition however, engineering education must also consider those subtle changes occurring in the social system, the changes in the needs and wants of the "end user" (consumer), and the changing needs and desires of the engineering professionals. All of these variables place fundamental constraints on the continued development of the engineering education program, and specifically on the engineering design element.

In the past, students graduating from traditional engineering programs were generally well founded in math and physics, and possessed reasonable procedural engineering analysis skills. They had been exposed to some liberal arts, and may have had some teamwork experiences in some type of engineering capstone design course. The educational process however was fundamentally directed at using the student's mind as a "storage facility". The resulting problem

solving techniques that developed from this approach often became the mechanical "plug & chug" approach to the engineering process.

High on the ABET 2000 list of "The Requirements for Engineering Graduates" are requirements that the graduate posses the (#2) **"Ability to design** and conduct experiments" - - - -, and (#3) the **"Ability to design** a system, component, or process" - - -. The development of a sequence of design learning experiences, continuing throughout the engineering curriculum, addresses these requirements directly, and provides the opportunity for the student to develop new ideas, and the ability to turn these ideas into reality.

As this sequence of design activities was being developed, several assumptions about the nature of the student had to be established. Paramount in these assumptions were those concerning the foundational skills that the high school graduate had to bring to an engineering program to be successful. For example, it was assumed that today's entering freshman engineering student possessed reasonable high school level communication skills. It was also assumed that they possessed reasonable social skills, and were capable of thinking and computing at a level appropriate for a high school graduate. It was therefore assumed, that it was with these foundational skills, that the entering freshman student approached engineering education, and specifically the engineering design process.

Having agreed upon the nature of the student, the second task to be completed in the development of this design experience sequence, was an agreed upon definition of "design". Further, if *synthesis* is the putting together of parts or elements so as to from a whole, then what are those parts or elements that make up the concept of *design*? What is "Design Synthesis"? In response to this question, it was generally agreed that the educational philosophies of Tykociner, Kotarbinski, Hannah, and especially Maccia, appropriately described the structure of man's knowledge, and specifically the concept of design [1]. The design concept could be portrayed as the total interaction of four fundamental theories:

1. **Form Theory**
   Explain a design concept in terms of:
   Form & arrangement - Mathematics & Logic,

2. **Event Theory**
   Explain a design concept in terms of:
   Physical Sciences, Biological Sciences, Social Sciences,
   Physics, Chemistry, Botany, Zoology,

3. **Value Theory**
   Explain a design concept in terms of:
   Good and/or right, and/or ethical, and/or beautiful,
   Fine arts & humanities,

4. **Technique Theory** (a study of technique theory would then be Technology)
   Explain a design concept in terms of:
   Clinical or professional subject matter:
   Engineering, Law, Journalism, Medicine, and Education.

It is therefore the total interaction of these four elements/theories that is considered essential in understanding engineering and the engineering design process. It is the synthesis of these four elements that is essential in making the concept of engineering design make sense. Whereas the intensity of the interaction between the various elements may differ in application to a specific design concept, the absence of any one of the four elements will make the concept incomplete and of limited use. It is the *presence and interaction* of the elements that makes the synthesis work.

II – STRUCTURE

The following sections of this paper describe how the design process has been incorporated into an undergraduate engineering program, both in design-specific courses, and as an integral part of theoretical content courses. This approach is based on the presentation of a number of open-ended design problems as exercises throughout the students' four-year educational career. The student has the opportunity to see a natural progression of design problems and problem solving techniques over a four-year undergraduate career. In some cases, a number of these problems are included in a dedicated design course. In most cases however, the problems are incorporated as exercises in courses aimed at presenting related theoretical material. Problems grow in technical complexity as the student progresses in technical sophistication. Students frequently encounter problems of communication and social interaction while working in a structured group setting. Group dynamics and team building skills are taught as an integral part of the design/problem solving experience.

The design experience sequence starts with an engineering course that is devoted to the design process specifically. The first course, which is an introduction to engineering design, is a required part of the first semester freshman year. The second course that is devoted entirely to engineering design, is the capstone senior design project, which is part of both semesters of the senior year.

There are also two other points in the students' educational career where required courses focus primarily on the design process. Both of these courses are outside the engineering program. They fulfill liberal studies requirements (are open to, or required of, the entire college) and are taught by engineering and technical/professional faculty. The first is a course entitled "Creative Design", which is taught by engineering faculty, and fulfills a fine & performing arts requirement. Content focuses on design as a creative solution to problems relating to industrial goods and processes. Required of all engineering students, this course addresses the concept of "Value Theory", specifically the *elements and principles of fine arts*, and their impact on the design process.

The second liberal arts course, which focuses on the design process, is an interdisciplinary course entitled Society, Ethics and Technology. Content focuses on how societies transform themselves through technological innovation. This course, which is also taught by engineering and technical/professional faculty, focuses on the principles of "Value Theory", specifically *ethical theories* and their application to the design process. All of the following design experiences, at all stages of the program, are designed with faithful adherence to the four elements of the design synthesis addressed above – *Form theory, Event theory, Value Theory, and Technique Theory*.

III – DESIGN IN THE FRESHMAN YEAR

Introduction to the engineering design process begins in the first semester of the freshman year with a course entitled "Fundamentals of Engineering Design". This course addresses the design process through visual communication techniques ranging from technical sketching through ProE, feature-based, parametric solid modeling. It also addresses the procedural aspects of engineering design from the reverse engineering process to an open-ended design problem.

The first design experience in this class is the reverse engineering analysis of a simple commercial product. This six-week activity entails the complete disassembly of the product, an analysis of how it works, the materials used, and the probable process of manufacture. Students are assigned to teams of three to four students. It is at this time, that the first discussions of group dynamics, of team development, and the interdependence of team members is held. This concept is further developed in future classes. The reverse engineering process is documented by a written technical report that is supported by sketches of parts and subassemblies, as well as sketched exploded views.

While this design experience going on, students also spend two hours per week in exploring the fundamental elements of the ProE engineering software. This experience continues throughout the semester, and parallels the design process.

The second design experience, in this Fundamentals of Engineering class, begins the seventh week of the semester, and entails a somewhat more complex, open-ended, design problem. The student groups are provided a limited number of parts (design constraints), from which they must design a product to perform some assigned task. Discussions, at this time, include an agreed upon design process. This process includes eight steps starting from problem analysis and framing a design brief to prototype development, and testing and evaluation. It is at this point, that the concept of assigning numeric values to design alternatives is introduced, and students are shown instances where these numeric values can be compared in the optimization of a particular design. A high level of interest in the project is maintained throughout the remainder of the semester by framing the end task as a competitive event between groups. Documentation for this activity includes a technical report, ProE parts drawings, ProE assembly drawings, and a project notebook documenting the groups work.

The second semester of the freshman year includes the Creative Design class discussed earlier. Since this class is a liberal studies, and draws students from various majors across campus, the assignment of design teams provides for truly heterogeneous groupings. Each group has at least one engineering major. The group dynamics process is covered once again from this new vantage point, and the steps of the design process are reiterated. For the engineering members of these groups, this material is the reinforcement of concepts encountered in the previous semester, and it provides the opportunity to utilize the concept of the interdependence of team members to capitalize on the unique contributions available from this interdisciplinary grouping.

Once again, the teams are provided with a limited number of materials (design constraints), from which they must design a product to perform a predetermined task. This is a semester-long term project in which particular attention to the part that *Value Theory* plays in the design process.

Therefore, the final product is judged not only on its performance, but also on its aesthetic/marketability value. Again, a competitive event is employed at the end of the semester to determine the level of performance of each teams product, and to maintain a high level of interest in performance development.

IV – DESIGN IN THE SOPHOMORE YEAR

The first semester sophomore year includes an engineering class in Manufacturing Processes. This class includes both lecture and laboratory experiences to provide an introduction to the basic tools, processes, and materials of manufacturing. The design elements of manufacturing process are developed through an open-ended, reverse engineering, term project. This project emphasizes organizational systems, plant layout and design, production and inventory control methods, quality control, marketing , and finance.

Since students in the class represent several engineering concentrations, the opportunity exists to assign group members from various engineering disciplines. An inter-engineering-disciplinary group if you will. The documentation of this activity includes a formal team presentation supported by high level visuals, and a technical report (group effort) that includes:

a) both parts and assembly drawings including packaging,
b) a product structure tree and indented bill of material,
c) route sheets
d) a parts list with costs,
e) a break even chart specifying labor costs, materials costs, overhead and sales,
f) and a critical path network

This design exercise addresses all of the elements of the design synthesis, the formal and descriptive theories as well as the prescriptive and technical theories. It is conducted in a manner which addresses the eight identified steps specified for the design process.

By the second semester of the sophomore year, students must have decided on their areas of concentration in the program. It is in this junction when they first experience courses designed for their specialty. By now, it is expected that they have gained an appreciable level of maturity in mathematics and sciences and have been exposed to some fundamental engineering courses.

To illustrate the typical level of design activities incorporated in the remainder of the curriculum, the authors have selected to concentrate on the format of the *mechanical specialty* of the program (as an example).

In the Mechanical Concentration, a course in “Mechanics of Materials” builds on the design momentum gained in the previous three semesters. The course challenges the students with wide array of design project. The projects are handled by groups of 2 or 3 students. Formal reports and presentations are required. A commercial software (c^2 b^2) is employed for analytical optimization exercises (iterative design).

A second course, “Mechanical Engineering Laboratory I” is conducted in the same semester. This course requires the design of an experiment by student groups. A formal report and presentation is also required.

In both courses, the elements of technical writing and group dynamics are further reviewed and exercised.

The following table displays the strategic allocation of the design activities/projects throughout the four-year period for the *mechanical specialty* of the program. Counterparts of such a chart may be generated for other specialties of the program.

Course Title	Year Taken	Term Taken	Nature of the Design Activity/Project				
			Design Problems	Mini-Design Project(s)	Final Design Project	Reverse Engineer.	C.A.D.
Fund. Eng. Design	**1**	**1**			✔	✔	✔
Creative Design	**1**	**2**	✔		✔		
Manufacture. Process	**2**	**1**				✔	
Mech. of Materials	**2**	**2**	✔	✔	✔		✔
Mech. Lab I	//	//		✔			
Soc. Ethics & Tech.	**3**	**1**			✔		
Adv. Eng. Math. II	//	//	✔				✔
Mech. Design Anal. I	//	//	✔	✔			
Thermodynamics. II	**3**	**2**	✔		✔		
Fluid Mechanics	//	//	✔		✔		
Kinematics & Mech.	//	//	✔	✔	✔	✔	✔
Mech. Lab. II	//	//			✔		
Heat Transfer	**4**	**1**	✔		✔		✔
Control Sys. Lab.	//	//			✔		✔
Mech. Lab III	//	//					✔
Computer Aided Des.	//	//	✔				✔
Senior Project I	//	//	✔		✔		✔
Mech. Lab IV	**4**	**2**			✔		✔
Mech. Elective	//	//	✔				✔
Senior Project II	//	//	✔		✔		✔

Table 1: Evolutionary Process of Distribution of Design Activities in the Mechanical Specialty of the Engineering Program at the College of New Jersey.

V – DESIGN IN THE JUNIOR YEAR

As seen in table-1, in the two semesters of the junior year of the mechanical concentration, there are seven courses that incorporate design exercises in a diversified manner.

The Kinematics and Mechanisms course, specifically, contains the highest level of design activities. In this course, students start their challenge with a variety of open-ended mini-design projects that include some degree of information research. A series of reverse engineering exercises expose the students to the world of working mechanisms. "Working Model" and its immense analytical and modeling capabilities are introduced here. A final design project requiring the complete design of a mechanism/machine brings the full spectrum of design criteria to closure. Applications of the Working Model are an integral part of the final design requirement. Some of these final projects will serve as the prelude for identifying an appropriate Senior Design Project in the senior year.

Oral presentations are a necessary part of the above projects. The collective presentations of all the students in the class would enable the students to see and learn about the thinking process and strategies of each other. They should realize there are many different methods of solving a design problem. This can only help to broaden and improve their own thinking processes and strategies [2].

Design activities in the remaining six courses of the junior year further enhance the design capabilities of the students.

Upon completion of the above projects, the students should have gained the knowledge, confidence and maturity to understand the elements of solving a design problem. The students should have reviewed the design process as presented in the freshman and sophomore years. They should have added to their knowledge of the design process. Most importantly, the students will have accomplished this independently, with limited advice and guidance from the instructor. The need to work within a group and ability to solve the problems of communications and coordination should be in place. The processes of conducting research and its benefits have also been experienced. The students should be ready to begin the work on their senior year capstone design project [2].

VI – DESIGN IN THE SENIOR YEAR

By the senior year, students have attained a sophistication and confidence to work on a design project requiring two semesters to complete. They understand the interdisciplinary nature of most systems. They understand that when starting a project, they will not have all the information necessary to successfully complete the project, and that they will have to research the information necessary for a successful design solution. Students have had numerous opportunities to work in groups, and understand their role in the group structure.

The two-semester senior design project is the capstone engineering design course meant to review, reinforce, and tie together all the previously learned concepts of design. The students use

the full two semesters to work on one design project of their own choosing. These projects are primarily group efforts with students drawn from several different engineering disciplines. One member of the group is usually from the engineering management concentration and serves as the team manager. This provides structure, organization, and time management of the group's efforts. There are at least two technical faculty advisors, and often a third advisor offering assistance specifically in team management.

Prior to signing up for Senior Project I, the student/group prepares a "Project Proposal". This proposal includes the formulation and statement of the design problem, and provides a general description of the planned approach to the design activity. It also specifies the outcomes and deliverables. The proposal also specifies the faculty members who have agreed to formally advise the project, and the basis upon which Senior Project I and II will be graded.

At the end of the first semester (Senior Project I), a preliminary design report is submitted along with a formal preliminary design presentation. The written report redefines the statement of the problem, the analysis of the problem, and a preliminary design of the system. The report includes:

a) Formulation and statement of design problem. Identify needs to be satisfied. Establish standards by which to judge suitability of the concept.
b) Evidence of a literature search in which you review the literature that is relevant to your topic.
c) Identification of constraints and standards established.
   These include (as appropriate to the project):
   - Economic Factors
   - Aesthetics
   - Reliability
   - Safety
   - Ethics
   - Social Impact
d) Detailed Description of System, Component or Process.
e) Project Specifications (Preliminary).
f) Discussion of constraints with accompanying analysis showing how the constraints related to the project specifications affect the design, and that the design accommodates the specified constraints.
g) Discussion of Feasibility Considerations.
h) Identification and discussion of alternative solutions, if any, and reasons for not choosing them.
I) Supporting documentation including plans, graphs, tables, etc.
j) Detailed prototype construction plan or schematic diagram.
k) A plan for testing the model or prototype developed.
l) A plan for evaluating the performance of the model or prototype.

The second semester of the senior design project (Senior Project II), typically includes the final design decisions, and design execution. In the large project efforts, which include some form of intercollegiate competition, the project manager and faculty advisors are heavily involved in raising funds to finance the project as well as team travel expenses to the competition venues.

At the end of Senior Project II, there is another formal "Final Design Presentation". The length of this presentation is based upon the number of students involved in the design group. These

presentation are open to the public and are attended by students and faculty and often by members of the Engineering Department's Industrial Advisory Council. These presentations are video taped, and the tapes are maintained in the departmental library.

The final written design report is also maintained in the departmental library, and used as reference material for future students involved in similar research. This "Final Design Report" includes:

a) Letter of transmittal
b) An abstract (200 words)
c) Review of the literature
d) Discussion of the following considerations and constraints:
   ethics, economic, reliability, safety (must be included in your discussion),
   aesthetics, social impact (include as appropriate to your project)
e) Deviation of specifications from the problem statements and problem constraints
f) Theoretical analysis of the design, any software evaluation, and experimental verification
g) A detailed discussion of your results. This discussion must include an analysis of your design and a description of the analytical model used and any limitations of the model with any error analysis
h) A presentation of the results of the overall design evaluation
I) Conclusions
j) Appendices

VII – CONCLUSIONS

It is the purpose of this paper then, to suggest that *a sequence of progressively more complex design experiences* be established as part of each level of academic preparation. Further, it is suggested that these design experiences be based upon *a well-founded definition of the nature of design*, and that the design experiences reflect this foundation. It is further suggested that *the steps of the design process* be firmly established, and that each design experience recognizes the validity of this process as it progresses. Early analysis of the graduates of this program seems to indicate that they are measurably better prepared for engineering leadership and management positions, and, those who wish, are accepting the most sought after graduate study fellowships. As the program develops, the view from the inside is that it can only get better.

The following table displays the performance record of the students in the mechanical specialty of the engineering program at the College of New Jersey in regional, national and international student design competitions. The involved students were among the first two generations of students/graduates who experienced the new design environment.

Year	Competition Title	Competition Level			# of Schools	TCNJ Placement
		Regional	National	International		
1999	Mini-Baja, Eastern Region	✔			40+	Top Ten Overall
1999	Solar Splash Solar/Electric Boat Regatta			✔	40+	Rookie Team with Best Overall Score
1999	Annual Great Moon-Buggy Race		✔		30+	AIAA's Best Engineering Design Award
2000	Mini-Baja, Eastern Region	✔			40+	Top Ten Overall
2000	Solar Splash Solar/Electric Boat Regatta			✔	40+	2nd. Place, Technical Report * Best Visuals
2000	ASME Student Design Contest Region III	✔			15+	2nd. Place
2000	Annual Great Moon-Buggy Race		✔		30+	1st. Place; National Championship

Table 2: Performance Record of the Students in the Mechanical Specialty of the Engineering Program at the College of New Jersey in Regional, National and International Student Design Competitions.

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NORMAN L. ASPER

Norman Asper is a Professor of Mechanical Engineering at the College of New Jersey. Professor Asper is an active member of ASME and ASEE and SAE. He has participated in the generation of the Safety Regulations for both the Solar Splash International Student Design Competition and Tour deSol. Professor Asper has degrees from Ball State University and Ohio State University.

BIJAN SEPAHPOUR

Bijan Sepahpour is an Associate Professor of Mechanical Engineering at the College of New Jersey. He is a Registered Professional Engineer and is actively involved in the generation of design-oriented exercises and development of laboratory apparatus and experiments in the areas of mechanics of materials and dynamics of machinery for undergraduate engineering programs. Professor Sepahpour is an active member of ASME and ASEE and has published in the proceedings of these societies. He has degrees from the College of New Jersey and New Jersey Institute of Technology.