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Curriculum-Integrated Engineering Design and Product Realization*

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In 1991 we began a major change in educating engineering students at the University of Maryland. We reversed the classical sequence of teaching mathematics, science, engineering science, and then finally design. Our teaching methods were changed dramatically from large lecture classes to small classes taught by an instructor who coaches more than lectures. The framework is extremely robust, and it has become an exportable platform for course development across the country. We believed that through re-engineering our educational programs, including the vertical integration of the product realization process throughout the curriculum, we could add sufficient value to our graduates' educational experience that will enable them to compete in the increasingly international engineering marketplace. Among these curriculum changes within the Clark School, we selected four pivotal courses to highlight in this presentation: ENES 100 'Introduction to Engineering Design', ENME 371 'Product Engineering and Manufacturing', ENES 120 'Statics' and ENES 220 'Strength of Materials'.

INTRODUCTION

IN THE SPRING of 1991, Maryland began a curriculum revision effort that brought many more hands-on design and manufacturing team projects into the engineering curriculum. These efforts were aimed at improving our retention rate, by improving the students' vision of engineering, and improving the breadth of our engineering graduates. Today engineering colleges are developing strategic plans and assessment programs that describe their products (graduates) in terms of outcomes. Some of the important outcomes that we strive for in Clark School graduates include the following:

- a good understanding of design and manufacturing processes
- a good understanding of and total competence in team work;
- a strong understanding of engineering science fundamentals;
- a good communicator;
- a multi-disciplinary, systems approach to engineering design.

THE CORPORATE PARTNER: METHODS TO ACHIEVE DESIRED ATTRIBUTES

A good understanding of design and manufacturing processes

Hands-on design and manufacturing are the cornerstones of ENES 100 and ENME 371. Prior to 1990, students were only taught design as part of their capstone course, and they may or may not have had any exposure to manufacturing. With the revision of our curriculum, students are introduced to design and manufacturing as they enter college (by ENES 100); and these themes are carried through into the second year (by ENES 102 Statics) through the third year in ENME 371 and into the fourth year (by the traditional capstone discipline-specific design courses). Maryland faculty members are now also working on bridging the gaps between these courses: curriculum development efforts are underway to introduce team-centered design and build exercises into the Dynamics, and Strength of Materials courses and a first-year student Physics course. These courses will provide our graduates a continuum of opportunities to develop a rich understanding of the design and manufacturing processes.

ENES 100 is offered in sections consisting of thirty incoming engineering students, one faculty instructor, one undergraduate Teaching Fellow [1], and a technical staff of graduate teaching assistants (GTAs) that support all sections. A typical class of thirty is divided into teams of five or six students who embark on a journey through several phases of a product realization process. All teams from all classes work to develop a single product from a common generic product objective. Example products have included solar desalination stills, scales, windmills, human-powered water pumping systems, solar cookers, and wind-powered vehicles [2, 3].

During the first phase of the course, skill development is emphasized. Students work individually and collectively to build their skills in teamwork,

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engineering graphics, and spreadsheets. In addition, the first-year students are introduced to the product realization process and some fundamental engineering principles. This need for teaching a diverse set of skills is handled by a team of instructors. Faculty, teaching fellows, and GTAs combine to teach this breadth of skills during the course's first phase.

During the second phase of the course, student teams formally focus on design. They work from the stated generic product objective to define their product specifications and constraints. Critical thinking is stressed. Safety considerations are addressed. The teams also learn about design critique, as they are asked to evaluate other teams' designs. Phase two culminates in a formal design review to the class and a complete design package including drawings, design analysis, costs and a descriptive report.

The third phase deals with manufacturing the components and assembling the product. Student teams must start with their own design package and manufacture and assemble their product. This is where 'the rubber hits the road,' and students are awakened by the realities of the difficulty of real-world design.

The final phase of the course consists of product testing, product evaluation, and the concept of scale-up. Each student team has a scheduled test period in which they must subject their product to a specified test procedure, previously defined by the faculty and technical staff. For example, in 1992–93, students tested their electricity-generating windmills in the Glenn L. Martin Wind Tunnel on campus. During the test, the students measure data that indicate the performance of their design, e.g. electrical output for a variety of electrical loads and wind speeds. While there is no formal emphasis on competition, the students are very concerned with the performance of their prototype and how it compares to those of their classmates. The students then revise their design packages to reflect the actual products as built and analyze their performance data. The final examination is a formal presentation in which the teams submit their revised design packages and orally present a final review. Also, they usually are given a scale-up question, e.g. how would you design a windmill to produce enough electricity for a dormitory?

The goal of the course is to provide a diverse nurturing learning environment to master the fundamentals of design methods.

Product Engineering and Manufacturing, ENME 371, is a new course designed to follow the first-year student design course with another even more significant experience in the product realization process [4]. The concept is to build on the first design course, but to consider as a case study a real product that is mass produced by a local company competing in the global market. This course is to be included in the revised mechanical engineering curriculum as a second semester offering in the second-year or in the first semester of the third-year. While the course has been developed for mechanical engineering majors, the content is broad and is suitable for students in any engineering discipline.

In ENME 371, each team is given two assignments: a group study on a manufacturing topic and a redesign project. The manufacturing study concludes with each team lecturing a full class period on their assigned topic, such as:

- injection molding and die casting;
- manufacturing shafts and gears;
- windings, armatures and stators of electric motors;
- design for manufacturing and assembly;
- assembly lines and cell systems;
- bearings and bearing manufacturing.

This is an example of students teaching students in the classroom. In the redesign project, each team concentrates on one or two features of the product, e.g. a sander, that they believe worthy of improvement. The students are expected to perform several of the following steps in implementing their ideas for improvement: analyze the design, build a mock-up, perform tests when possible (thermal, acoustic, vibration, etc.), analyze the cost benefits, and demonstrate their work. Topics have included a redesign of the dust collection system, improvement in the fan system, redesign of the sanding pad, reduction of the electrical connections during assembly, redesign the shroud for easier grip, and standardize the number of screws and other parts.

The corporate partner is an essential element in a course with these objectives. The content covers the product realization process from its inception to product release to the market. It is essential that classroom discussion be based on a real product and that abstractions are avoided. The corporate partner can provide the crucial information about the history of the company, its culture, the organization of the development team, and the many experiences involved in the development process. Black & Decker has been the corporate partner since the first pilot offering of this course in Fall 1994.

A good understanding of and total commitment to team work

The Clark School of Engineering has implemented a significant increase in the use of team work (both on the part of the students and the faculty) to develop a world-class college of engineering. Prior to 1990, students may have only participated on teams in their engineering laboratory courses and in their capstone design course. Today, team work is critical in many more courses. Likewise before 1992, faculty members rarely had to participate in teaching teams. Today's team-centered hands-on design and manufacturing courses also require faculty members to function in teams.

The courses' outputs require team-based performance, rather than individual performance. For example the projects are sufficiently complex and time-consuming that an individual student cannot complete the necessary work; the projects cannot be completed without functional teams. Furthermore, significant portions of the student grades are based on the team's performance, and for the fourth-year course, on a peer review. Good team work is critical for success in these courses.

Our college has also learned that large, distributed, and complex processes can only be run effectively by using multi-disciplinary teams of teachers, who come from the academic and the industrial communities. For example in ENME 371, classes are jointly taught by one or more faculty members and several industrial product specialists. The faculty 'instructor' is more like a team leader in an industrial setting than a traditional lecturer. The instructor does teach a number of topics such as probability and statistics, but he/she facilitates the entire process. Technical experts work with the student teams at appropriate junctions of the term; these experts have come from industry and from within the college. For example, six Black & Decker engineers came to give class presentations on six dates; and the College's Director of Total Quality Management gave a presentation on another date. As observed by the *Graduating Engineer* [5], 'A teaming of academia and industry, the course utilizes the best of both to teach everything from hands-on processes, such as product redesign, to sophisticated business concepts, such as Total Quality Management (TQM) . . .'

A strong understanding of engineering science fundamentals

These courses serve to motivate the students to appreciate the fundamental material taught in engineering science courses and to give students the opportunity to apply their theoretical knowledge. In ENME 371, the students apply the mechanics of balancing the rotational motion due to the eccentric offset of a random orbit sander, gain an understanding of the operation of an electric motor, and apply the principles of fluid motion in examining the fan that is used for cooling and for the dust collection system.

In ENES 100, the technical content required to analyze the design of the product is taught just-in-time. The students are encouraged to ask their instructor to explain where in the curriculum they will gain the expertise to make such a decision with more confidence. By showing the students the need for engineering science fundamentals first, the students later seize the available opportunities. For example, one statics professor was quoted, 'I've never seen students so motivated to take statics in 30 years [since the start of ENES 100].' As they will learn about different branches of engineering, students come to view the curriculum as a series of learning opportunities, rather than hurdles, toward a degree.

A good communicator

Excellent communication skills, i.e. speaking, writing and graphics, are stressed throughout the curriculum. Students make at least two major oral presentations in ENES 100 and ENME 371. For ENES 100, the oral presentations are the preliminary design review and the final design review. For ENME 371, the oral presentations are a complete lecture on a manufacturing process and the final redesign proposals which are presented to an audience composed of students, faculty, and Black & Decker engineers. The student presentations are videotaped so as to allow the student presenters to view the tapes to improve their presentation skills. Teams receive written critiques from their classmates (anonymously) on their presentations.

These courses have a major final design report; ENES 100 also has a major preliminary design report. The courses also rely on the use of intermediate writing assignments: team progress reports, team journals, technical notes, and in-progress documents. Graphics are emphasized.

A multi-disciplinary, systems-perspective to problem solving

These courses force a systems-perspective by using a 'complete' product development process, i.e., the students must take a product from its idea phase to manufactured product. Students no longer focus on individual parts at the expense of the entire system. For example, in our previous first-year engineering course, students spent weeks drafting machine components, but never considered the system in which these parts were used. Now our students consider the systems, and then the components which comprise the systems.

The approach in these courses is summarized in an article in *Graduating Engineer* [5], '. . . you actually learn how an engineer works in various different areas. It's a holistic approach, and that's what makes it so great.'

An understanding of the context in which engineering is practiced

These courses place far more emphasis on the context in which engineering is practiced than its predecessor courses. For example one of the basic objectives of ENME 371 is to introduce some of the business aspects in the product realization process. We introduce the business side of the design and manufacturing processes by showing organizational structures in a typical product-oriented company and emphasize the profit motivation associated with new products. This discussion exposes the students to:

- the representation and coupling among engineering, marketing, finance, purchasing and manufacturing;
- the importance of the interaction between marketing and engineering design in the evolution of a product;

- the importance of the physical location of team members that can significantly affect communication and time required to develop a product.

The lectures by Black & Decker personnel expose the students to the role of an engineer in a company in the product development business, not only in terms of the technical skills required but also in the engineers' interaction with other non-engineering members of the company.

An ability to think both critically and creatively—independently and cooperatively

These courses use open-ended product development examples to foster critical and creative thinking. Creative thinking, both independently and cooperatively, is needed just to define the problem and to develop possible solutions. The critical thinking element comes into play as students narrow their possible solutions into the final design or redesign proposal.

SUMMARY

The Maryland team of senior and junior faculty and staff have developed a process in which critical engineering design and manufacturing skills are introduced to engineering students. This process employs a team of faculty, graduate students, senior undergraduate students, and staff to create a diverse learning environment in which engineering students participate in product realization processes. During these quests, students come to realize the importance of the engineering curriculum. They are introduced to a wide range of engineering skills required for a sound professional life. The results of this program have been overwhelmingly positive, as measured by customer surveys and focused interviews. The ENES 100 course model has also proved very effective as an outreach vehicle; outreach programs are underway at numerous four-year and two-year colleges and a high school, and more programs are being planned.

Two major outcomes of our efforts have been textbooks [6–11] and faculty development programs. A strong assessment protocol is built into all of these courses. Frank L. Huband, Executive Director of ASEE, has summarized the effect of Maryland's program early in its development in an editorial in the May 1993 issue of *Prism* [12], 'Maryland design projects represent the beginnings of a revolution—or maybe something more like a quest—to reform engineering education.'

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