Int. J. Engng Ed. Vol. 17, Nos. 4 and 5, pp. 375–380, 2001
Printed in Great Britain.

0949-149X/91 $3.00+0.00

SynThesis: Integrating Real World Product Design and Business Development with the Challenges of Innovative Instruction*

ROBERT E. APFEL and NATALIE JEREMIJENKO
Department of Mechanical Engineering, Yale University, 9 Hillhouse Ave. New Haven CT 06520, USA
E-mail: robert.apfel@yale.edu

SynThesis: Product Design and Business Development for Entrepreneurial Teams is a new curricular offering at Yale University that brings together engineering, computer science, and management students into entrepreneurial teams to create new products and business plans. The evolution of the design of this full-year course is described herein, including the objective of orienting the course deliverables to product-based learning; the use of external validation and peer evaluation; close relationships with industry; privileging a team-based reward systems; reinforcing collaborative learning and problem solving; delivering just-in-time course materials; and aligning projects and self-assembling teams with the concerns of the students. The paper also elaborates on methods of course assessment and student and team self-assessment.

INTRODUCTION

WE JUST COMPLETED the first year of a new graduate-level course emphasizing product design, business development, and team process. In this course we implemented and tested many of the published ideas of the engineering design community on integrating project-based engineering design into the formal engineering curricula [1]. These include:

- orienting the course deliverables to product-based learning
- the use of external validation and peer evaluation; close relationships with industry
- privileging a team-based reward systems
- reinforcing collaborative learning and problem solving; delivering just-in-time course materials
- aligning projects and self-assembling teams with the concerns of the students.

We report on the results of the course, our experiences, and the feedback from the students, industry participants and faculty (and interactions at the workshop) that is enabling the teaching team to develop the strategies, discussed herein, to improve the course.

CREATING SYNTHESIS

The Faculty of Engineering has introduced a new 4 + 1 Select Program in Engineering, which yields a Bachelor of Science degree in an engineering field, applied physics, or computer science (CS), and a Masters of Engineering (or Science, for CS) degree. The program requires that a student:

- achieves a prescribed grade-point average;
- takes an adequate course load in design;
- supplements their undergraduate degree program with courses in the management sciences, economics, ethics, and environmental engineering;
- and gains six months of practical experience in industry (usually through internships after the junior and senior years).

In the graduate phase of the program students take advanced courses in engineering and management-related courses, and a full year product design and business development course called SynThesis, bringing engineering, computer science, and business students together into teams. This project requirement differs from many traditional theses in its themes of integration of experience and in the emphasis on team building and performance. The course design responds to input from our industry advisory board and the inadequacies in engineering graduates reported by industry [2].

In conceiving SynThesis, a team of faculty met throughout the year to address a number of fundamental questions. The discussion informed the specific goal of the course:

1. To build a realistic real-world experience of product design and business development.
2. To motivate students.
3. To provide a web of information, support and wherewithal into the process, thereby assuring a positive educational experience.

* Accepted 27 November 2000.

In the context of this goal were underlying questions:

- What are the critical differences between the educational experience and the real-world context?
- What pedagogical approaches encourage team enthusiasm and cohesiveness, and give the teams the building blocks necessary to conceive and create within the context of real world needs?
- What preparatory design exercises draw the non engineers into the design activity?
- When do and how can business considerations motivate engineering students and impact the design?

Educating students in product design and development involves addressing several contexts of the professional practice of product design: working within large corporations, working in design firms, or working as independent entrepreneurial teams [3] (Kaplan, 1998). The teaching team chose to focus on providing the experience of the last of these, i.e. entrepreneurial teams, rather than the more traditional focus on design engineering for clients or the detailed engineering involved in iterative innovation typical in corporate product development. The reasons for this choice were:

- independent entrepreneurial teams produce more 'discontinuous' innovation;
- the university environment cannot simulate the corporate or design firm context, and while industry participation is invaluable, it can conflict with the students' control in problem definition and implementation;
- many engineers will find employment in corporations or design firms; the skills involved in self-managing entrepreneurial innovation are applicable to these design contexts. Innovative opportunities for careers that are independent of corporations and design firms are greatly expanding in the current economic conditions.
- an explicit commitment to educating students with the skills to lead technological innovation predisposes the teaching team to give the students leadership experience.

Consistent with research examining the background of contemporary technological innovators, while most have engineering educational backgrounds, they actually work in non-engineering roles. [Studies that have examined the educational background of contemporary technological innovators including Kaplan 1998 show that while engineers founded most innovative technology companies, most of these successful engineer-entrepreneurs lament the lack of introduction to financial, marketing and management issues in their formal education.] Providing students with the experience and confidence to self-manage a project entirely gives them experience in the multiple roles involved in product development.

Our secondary but explicit goals then are:

- to provide entrepreneurial leadership roles for engineers, to engender in students confidence to initiate and carry out design projects;
- to provide the experience of incorporating technical and non-technical considerations into the physical design of products;
- to inspire the students with approaches that go far beyond current teaching and learning strategies and that extend and integrate engineering knowledge across disciplines and throughout the market to provide the individual with the capacity to pursue the career of their choice.

Since product development is cross-disciplinary (even anti-disciplinary) involving matters that transcend traditional engineering, it was essential to introduce instruction related to management, finance, and social sciences. Lectures on marketing, business planning, ethnographic methods, cultural theory, and group processes were essential components of the course. For these lectures, we turned to faculty and graduate students beyond engineering from the Yale School of Management and the Psychology Department.

The nonlinearity of product development, involving feedback and concurrent engineering, required the instructional process to mimic this process. Students are accustomed to linear courses and the compartmentalization of subject matter and grading. Many want to receive an assignment and a deadline and will independently complete these. Within product design and development, individuals have to depend on their fellow team members to finish an assignment. Cooperative learning can improve the success of solving difficult design problems [4]. However, it is critical that the assessment reinforces the team responsibility and performance over the individual's performance, and the project outcome over the individual assignments in product-based learning. [Coined by Leifer, this adapts the virtues of project based learning (PBL) educational reforms to the specific requirements of design engineering.] To this end, the team's autonomy is reinforced with respect to the faculty[5] by involving students in defining, scheduling and prioritizing the assignments and milestones. Portfolios, team and individual grades, and jury assessments were initiated in SynThesis and will be further developed in the future.

CURRICULUM ELEMENTS

The structure of the full-year course was loosely in four parts, returning to each of the topics several times:

1. Introduction to the product design and business development process (including mini projects, team and product selection).

2. Project definition and prototype development in the context of needs assessment.
3. Business planning.
4. Product refinement and manufacturing planning.

Initial phase

The intention of the preliminary design exercises was to give the students rapid feedback from their peers and the chance to produce 'quick and dirty' design, jolting the students into the hands-on development required in the course. Database problems delayed the peer feedback, (which was made anonymous by web-based feedback forms). This information is very time sensitive, and we learned that if delayed, the value of this information diminishes immediately.

The most successful of the initial exercises was the voice chip project. The student designs, given only two weeks to design and implement a fully functional voice chip-based application, were all successful and potentially viable products. It was also a project in which they could draw on their own 'use' expertise. The designs were innovative, widely varying and fully functional. We suspect that one reason for the success of this design exercise is that while the hardware was simple and modular, it also provided students tangible functional prototypes that verified the usability and feasibility of the products. Another exercise, 'benchmarketing', that combined product benchmarking with analysis of marketing issues was less successful. The exercise built on the pedagogically proven [6] 'product dissection lab' activity, but the actual synthesis of the marketing information into the product picture did not work very well. The results were similar to the findings of Altman and others [7], in that students tended not to source the appropriate range of information (as compared to experienced designers or interested parties) or to bring this information to bear on the product. The extent and range of information used changed (with respect to the quantity of different sources used) when the students were working on projects of their own definition. Engineering and management students need extra support in searching non-technical information and in sorting through the many types of marketing information. The teaching team will address this issue in the future by developing several exemplar benchmarketing cases that will demonstrate the scope of analysis required and will break down the information components the students need to find. A forum called 'Product of the Week', for ongoing product analysis by individual students, will build a rich portfolio of products throughout the year.

Product conceptualization phase

This phase was the most critical in that it had enormous impact on the team performance throughout the rest of the year. The successful part of this process was that each student had to attract a team for their product idea. This meant that the product ideas were peer-evaluated and teams were self-assembled. When this works, it seems to guarantee the enrollment and enthusiasm of team members; however, for one team this process did not work. There may inevitably be a team of 'leftovers' who are not able to attract persons to their proposal. In trying to preserve a valuable educational experience for the students, we are trying to explore strategies that will preserve the high motivation associated with assembling teams in this manner, while not compromising the learning experience of the teams that were not able to converge on a product in the timeframe given. [See Delson discussion in this issue regarding the polarizing effects of project based courses.]

Business planning phase

The metaphor for business planning was writing a good story, where 'good' story means that it is believable (supported by solid marketing research and product definition), and there is a happy ending for all involved (including the team, its investors, and the consumer). The 'product story' forced the students to revisit the engineering design problems and present them as 'word problems', which encouraged new approaches [8]. The fact that there is a major Connecticut Venture Group Business Plan competition for academic institutions that overlaps with the time of this phase, was an extremely effective motivator. Although our teams performed very well in this, we believe that they need additional support in financial analysis tools. Considering the financial analysis, students did not revisit any of the designs nor effect of tradeoffs, indicating this shortcoming and demonstrating that the students did not 'believe' their own financial stories. [A useful comparison is the performance of SynThesis teams vis-à-vis the performance teams constituted entirely by business school students. The entries were predominantly from business student teams and the proportion of Synthesis teams (2/3 versus 1/15 at our institution) that made it to the finalists' stage validates our approach.]

In each of these broad phases, we adapted to the changing circumstances in an involuntary practice we call 'just-in-time-instruction'. The two class periods that occurred each week were divided into lectures and design studio time. The latter period enabled the students to work together, and to present material to their peers, faculty and invited guests. Without the organized studio space to promote the independent team activity (students used their own residences instead) the class time during the studio period was too short to accomplish actual building and prototyping activities.

A list of the assigned deliverables, once student teams began their major projects, appears in rough chronological order below. The list of deliverables was kept to a minimum so that the teams preserved independence to manage their own activity within the framework in which they were assessed.

Next to each category, we have abbreviated three categories:

1. Project Conception Phase (C),
2. Design and Design Documentation (D)
3. Business Planning (B).

Product definition assignment	C
Define user and appropriate interface and look and feel of product	D
Critical function review	C
define critical functions of product; and all functional parts	
Initial financial feasibility assignment—	B
determine thumbnail of financial market, initial cost estimates and general feasibility of the product	
look and feel prototype	C
design requirements document	D
post the design requirements document on the web	
functional prototype review—demonstrate critical functions in hardware	D
scheduling assignment	D
methodology review	D
1st user test results presented	D
alpha prototype	D
functional and look and feel	D
vendors list	B
resources and vendors and material	
parts drawings	D
present budget	B
financial analysis	B
final business plan	B
manufacturable prototype	D
design review	D
design requirements document	D
deliverables contract	
assembly drawing	D
final specifications	D
beta prototype	D
final pre-market user tests	B
final prototype	D
final presentation	
final design document	D
CT Venture Group competition entries	B
course assessment	

The team projects in 1998–99

1. The Ola-Factory, a computer peripheral that delivers scents from a multi-scent cartridge, either for computer gaming or aroma therapy applications.
2. The STAR Sprinkler Co., which developed a sprinkler system for conformal and programmable lawn area coverage.
3. Safe Overhead Storage, which designed a new pull-down overhead system for accommodating the growing storage needs of homeowners.

Each team had at least one engineering student and one student from Yale's Professional School of Management. There were four engineering students (three seniors and one masters student), three computer science students (two seniors and one graduate student), one biology and economics major (a senior), and three graduate students in the School of Management.

PEDAGOGICAL CHALLENGES

The major pedagogical challenges revolved around maintaining a real world context, while assuring a supportive learning environment. Some of the steps in this effort included: requiring students to use resources beyond the academic community (e.g. vendors, fabricators; focus groups of potential end users); coordinating an appropriate external jury for each presentation and for many of the deliverables; deciding when the industry voice should be brought to bear on the student projects; encouraging company participation more generally so that students had opportunities to improve the way they presented themselves to non-academics; and other internal team management issues that replicate real world issues such as the preparation of appropriate documentation for manufacturing.

How do students view instructors in this nonlinear product design process? Are they lecturers, graders, bosses, mentors, or pests? Since students respond to deadlines, instructors must somehow have a set of gradeable deliverables. At the same time, instructors want to instill in students the sense of the excitement of the process that transcends individual assignments and the undermining of autonomy that occurs by organizing the workload into assignments. At times this process is akin to the 'conditional chaos' that is inherent in the creative process. Rather than allowing anxiety to be the result of this uncertain process, the competencies developed in this course will enable students to engage product development and negotiate the productive tensions and tradeoffs in the process.

External validation

External deadlines are superb motivators and act as useful milestones. In addition, partaking in a number of design competitions (e.g., Aspen Student Design competition and ID Magazine Design competition), the course structured the business plan deliverables around The Connecticut Venture Group's Business Plan Competition for academic institutions. The CVG competition began at the commencement of the preparation of each team's business plan, first with an initial phase entry (to the number of statewide entries), and then two months later a full business plan was due. Each of the three SynThesis teams participated as a course requirement. Two made it into the finals, and one group—The Ola-Factory—won the $20,000 first prize. The competition was timed so that the winning team would be able to participate in Connecticut's annual Venture Fair, where venture capitalists and others are invited to hear entrepreneurs 'pitch' their company's new initiatives. Several hundred attended, and our winning team performed exceptionally well.

OUTCOMES AND VALIDATION OF PEDAGOGICAL STRATEGIES

Students and faculty in SynThesis were immersed in a creative process: the creation of a new course. The ingredients were all there:

- good design materials
- sound business planning,
- good interactions with a diverse faculty and with experienced industry leaders, etc.

Of course, the ingredients do not always guarantee a good meal. The methods of preparation are crucial. In many respects there were many lost opportunities for coherency (exacerbated by the diversity of the projects undertaken). For example, in the next teaching year many of the materials about the design process and the course expectations were assembled in a loose leaf notebook and provided to each student beginning the course to provide them with a shared set of references to build upon.

Our biggest shortcoming in the past year was not having a formal design studio space and adequate class studio time. This approach would allow instructors, acting as mentors, to observe and facilitate a regular weekly activity of each team, thereby reducing organizational overhead for the teams trying to coordinate places to meet and arranging for what team materials to have with them. A shared studio space will provide the stage for the many diverse interactions that constitute design activity (understood as a social process). This studio space is secured for the following year of the course.

Timely feedback by students (both self-assessment and team assessments) and by faculty is essential. This process is now being formalized into a web-based and anonymous assessment site, with quantitative data going into a database for analysis of longitudinal trends and for collecting feedback and reflection from the students at least seven times during the course. Further strategies to validate the pedagogical processes used in this course are being investigated and organized. The noun phrases metric developed by Mabagunje and others [9] is an exemplar for implementing a robust summative metric in combination with the portfolios discussed earlier but the overhead for this is beyond the teaching team at this time. As we develop a manageable system of validation, we will use the external opinions and competitions, student portfolios, product prototypes and the ongoing feedback from graduates as part of the diverse strategies with which to check our course methods and content.

Acknowledgments—The instructors are indebted to Nathan Delson, Peter Kindlmann, David Cromwell, Henry Bolanos, and Subrata Sen for serving on the SynThesis development committee and acting as jurors for the student presentations. Several other Yale faculty and representatives from industry were essential in providing students with resources and a real world perspective with which to conceive and develop their projects. Household Products Incorporated has been exceptionally generous with their time.

REFERENCES

1. A. J. Dutson, Robert H. Todd, Spencer P. Magleby and Carl D. Sorensen, A review of the Literature on Teaching Engineering Design Through Project-Oriented Capstone Courses. *Journal of Engineering Education,* **86**(1), (1997) 35–37.
2. D. L. Evans, G. C. Beakly, P. E. Crouch and G. T. Yamaguchi, Attributes of Engineering Graduates and Their Impact on Curriculum Design, *Journal of Engineering Education*, **82**(4), (1993).
3. G. Kaplan and T. S. Perry, Engineers as Entrepreneurs, *IEEE Spectrum*, **34**(8), (1998) p14, 10p, 14c.
4. N. J. Mourtos, The Nuts and Bolts of Cooperative Learning in Engineering, *Journal of Engineering Education,* **86**(1), (1997) pp. 35–37.
5. M. F. C. Brereton, M. David, Ade Mabogunje and Larry Leifer, Collaboration in Design Teams: how social interaction shapes the product, *Analyzing design activity*, N. C. Cross, John Wiley & Sons, (1996) pp. 319–340.
6. D. Sathianathan, S. Sheppard, R. Jenison, N. Bilgutay, J. Demel, P. Gavankar, J. Lockledge, R. Mutherasan, H. Phillips and J. Richardson, Freshman design projects: lessons learned in engineering coalitions, *1998 Annual Frontiers in Education Conference. Moving from 'Teacher-Centered' to Learner-Centered Education. Conference Proceedings IEEE*, **3**, (1998) p. 1121.
7. C. J. Atman, Karen M. Bursic and Stefanie L. Lozito, Gathering information: What do students do? *1994 ASEE Annual Conference Proceedings*, (1995) pp. 1138–1143.
8. J. Page, Michael Mulvihill and Joseph Callinan, Engineering analysis and problem solving, *1992 ASEE Annual Conference Proceedings*, (1992) pp. 1432–1433.
9. A. Mabogunje and L. J. Leifer, Measuring the mechanical engineering design process, *Frontiers in Education Conference,* November 1996.

Other relevant papers include:

E. W. Banios, An engineering practices course, *IEEE Transactions on Education*, **35**(4) (1992) pp. 286–295.

J. Bordogna, Connecting the parts, ASEE *Prism*. (1992).

J. Bordogna, E. Fromm, E. W. Ernst, Engineering education: innovation through integration, *Journal of Engineering Education*, Jan. (1993) pp. 3–8.

A. J. Boye, R. J. Soukup, and P. F. Williams, Teaching engineering as the science of solving word problems—Part II, *1992 ASEE Annual Conference Proceedings*, (1992) pp. 1534–1536.
R. W. Clinch, Affective engineering education, *1989 Frontiers in Education Conference Proceedings*, (1989) p. 202.

Robert Apfel is Robert Higgin Professor of Mechanical Engineering at Yale University, where his research focuses on ultrasonics, cavitation, nucleation phenomena, and materials science, and his teaching ranges from freshman courses in design to graduate courses on architectural acoustics and on product design and entrepreneurship. He has been President of the Acoustical Society of America, from which he received the Silver Medal in Physical Acoustics. He is currently the Editor of Acoustics Research Letters Online, a peer reviewed electronic journal of acoustics. He has recently published a book on architectural acoustics entitled: Deaf Architects and Blind Acousticians? A Guide to the Principles of Sound Design. He is also President of Apfel Enterprises, Inc., which designs and manufactures radiation detectors based on the nucleation by radiation of superheated drop compositions. These compositions are now being modified for possible application in targeted drug delivery. Apfel has about 140 publications in peer-reviewed journals and holds four patents.

Natalie Jeremijenko, 1999 Rockefeller fellow, is a design engineer and technoartist. She was recently named one of the top one hundred young innovators by the MIT Technology Review. Her work includes digital, electromechanical, and interactive systems in addition to biotechnological work that have recently been included in the Guggenheim Museum(1999), Whitney Biennial '97, and Documenta '97. She is currently a research scientist at the Media Research Lab/Center for Advanced Technology in the Computer Science Dept., NYU. and will be returning to Yale as an Assistant Professor and director of the Engineering Design Studio developing and implementing new courses in technological innovation.