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IME Inc.—A New Course for Integrating Design, Manufacturing and Production into the Engineering Curriculum*

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Senior capstone design courses and projects like the SAE Formula Car or Hybrid Electric Vehicle have been created to provide engineering students with 'real-world' and 'hands-on' design experience; however, the products being realized are often only working prototypes. Engineering students rarely have the opportunity to experience the entire product realization process, from designing a product to developing a manufacturing plan for it and subsequently producing it in volume. Consequently, we have developed a new two-semester undergraduate course, IME Inc., wherein multidisciplinary student teams design and develop a marketable product while considering all aspects of manufacturing—including process planning, tooling, assembly, outsourcing, and final costs—so that they can produce approximately 100 units in the Factory for Advanced Manufacturing Education. The objective in the course is to improve manufacturing engineering education by providing students with manufacturing and production experiences analogous to those obtained by journalism students working on a student-run newspaper. The course is taught jointly by five engineering faculty with expertise in product design, CAD/CAM, rapid prototyping, plastic injection molding, electronic assembly, and manufacturing systems design. Multidisciplinary teams consist of students in industrial and manufacturing engineering, students from other engineering disciplines (e.g. mechanical, electrical, and chemical engineering), and students from the business school studying marketing, management, finance, and accounting. The business students work directly with the engineers in analyzing product price, manufacturing costs, licensing issues, and developing a business plan and an e-commerce site to sell the products. Products designed, prototyped, and produced during the 2000 and 2001 offerings of IME Inc. are presented and discussed. Assessment strategies for evaluating team performance and the impact of the course on students' learning readiness are also presented. In particular, design notebooks and frequent design reviews are used throughout the course to monitor progress during design and production as well as evaluate team performance. To further enhance undergraduate education in manufacturing engineering, the course also focuses on creating a classroom environment that promotes self-directed learning, active and problem-based learning, teamwork, communication, and presentation skills. Individual learning essays are used to gauge students' understanding of the product realization process, while the impact of the course on students' lifelong learning abilities is assessed using the Self-Directed Learning Readiness Scale, a self-report questionnaire that is administered anonymously at the beginning and the end of the two-semester course. Lessons learned from the course are also discussed, along with plans for using IME Inc. as a 'living factory' to improve the broader industrial and manufacturing engineering curriculum.

INTRODUCTION AND MOTIVATION

JOURNALISM STUDENTS can run their own newspaper, communication majors can produce their own television or radio shows, and business students can create their own business plans, but where can engineering students who are interested in design and manufacture design and produce their own products *in volume*? Co-op is one possibility, but exposure to the intricacies of the product realization process is limited at best, and non-existent at worst, when spending so little time in an industrial setting. Senior capstone design courses and student projects like the SAE Formula Car or Hybrid Electric Vehicle have been created to provide engineering students with 'real-world'

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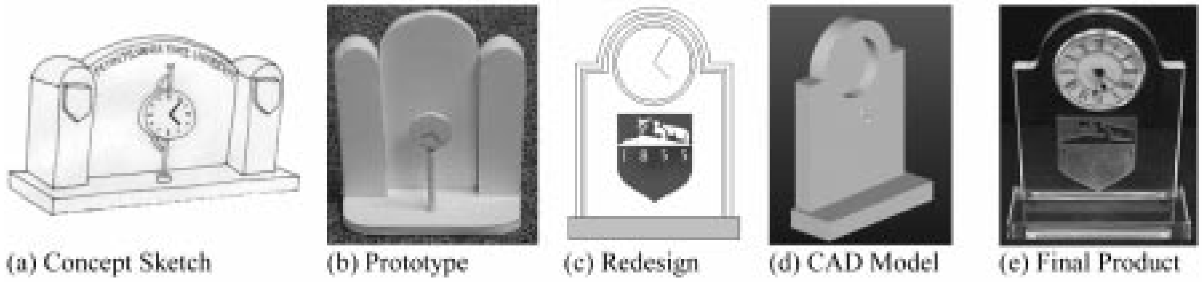


Fig. 1. A product at the various stages of the product realization process in IME Inc.

and 'hands-on' design experience; however, the products being realized are often only working prototypes. The Learning Factories at Penn State, University of Washington, and University of Puerto Rico-Mayaguez were developed to integrate design and manufacturing into the engineering curriculum as part of the Manufacturing Engineering Education Partnership [1]. Meanwhile, Shah *et al.* [2] describe a virtual corporation designed to simulate real-world collaborative design that involves building a product from scratch in a course. Even though many schools now offer two-semester senior design capstone courses (e.g. University of Missouri-Rolla [3], Rensselaer Polytechnic Institute, and Carnegie Mellon) or multi-semester engineering 'clinics' (e.g. Harvey Mudd College [4, 5] and Rowan [6, 7]), few engineering students experience the challenges of producing products in volume. Carranti [8] describes an undergraduate manufacturing processes course at Syracuse University that was revised to include a project where students mass produce a novelty item given to them by the instructor. A simple hands-on activity to compare and contrast craft production and mass production in the classroom using paper airplanes is described in Simpson [9].

In an effort to expose students to the entire product realization process—from conceptual design to volume production—while providing design activities for the 'missing middle years' [10], we have developed a novel two-semester undergraduate course called IME Inc., which integrates the traditional capstone design experience with hands-on experience in volume production and manufacturing. As one student put it: 'This course has exposed me to every part of this [the product realization] process, from concept formation to the completion of a production run. Having gone through this entire process, I now have insight on nearly every aspect of product development.' A description of IME Inc. is given in the next section, followed by an overview of our production facilities. Products developed in the first and second offerings of IME Inc. are then discussed, followed by an assessment of the student learning in the course. A summary of what went right and what went wrong is given in the final section, along with future course modifications.

COURSE DESCRIPTION

The primary objective of IME Inc. is to provide an integrative, hands-on experience in all of the elements of the product realization process, and Fig. 1 shows an example of a recent product at various stages of this process. An additional objective is to develop students' competence in essential on-the-job skills, including teamwork, project management, independent learning, vendor relations, problem solving, and effective communication. The course is delivered as a two-semester sequence, where the first course is offered each spring and is targeted at junior year IE, ME, and EEME undergraduates. The intention is to provide students with a significant engineering experience early in their major course sequence to engage their interest in other courses that offer formal instruction in the processes and techniques to which they are introduced in this course.

The first semester of IME Inc. covers product design, while the second focuses on manufacturing process design and production. In the first course, students are given a general charge (e.g. develop a product that utilizes a programmable LCD assembly or has moving parts), and the students work in multidisciplinary teams to accomplish the following tasks:

- identify customer needs;
- develop and select a design concept;
- produce a detailed design (CAD model and rapid prototype);
- develop cost and selling price estimates; and
- create an initial manufacturing process plan.

During the second course, students implement the manufacturing plans developed in the first course. In particular, the students:

- refine their process plan;
- conduct a pilot production run;
- modify the design and process as needed;
- purchase materials and supplies;
- conduct a production run of approximately 100 items; and
- develop an e-commerce site and business plan to sell the products.

IME Inc. is unique in several ways. First, the course ties together design and production—students must confront issues related to volume production and can observe the influence of design decisions on final product cost. Second, it is targeted at junior-level students (IE, ME, and EE) who learn 'on the job' versus applying what they already know. Third, engineering students work directly with business students to do benchmarking, customer surveys and marketing, cost analysis and cost reductions. Finally, we stress the importance of documenting and archiving design and manufacturing information—design work occurs in the spring, while production does not start until the fall semester after students return from their summer break.

The course is jointly taught by five engineering faculty with expertise in product design, CAD/CAM, rapid prototyping, plastic injection molding, electronic assembly, and manufacturing systems design. An instructor from the business school assists the teams with marketing, financial, economical, and licensing issues. The majority of class time is spent working in teams, with the faculty acting as coaches. The faculty critique student designs, offer alternatives for the students to explore, answer their questions, and suggest resources for obtaining answers in areas outside of faculty expertise.

Lectures are delivered 'just-in-time', taking the form of workshops on specific tools or methods (e.g. brainstorming techniques, Pro/Engineer, MasterCAM) as needed. Industry speakers are utilized sparingly during the first semester to provide perspective on the product design process and on design for manufacture. Plant tours (e.g. foundries, injection molding facilities, etc.) are arranged, as appropriate, depending on the products and production processes contemplated by the student teams. The students are expected and encouraged to develop solutions to their problems using a variety of resources, including the faculty and technical staff, websites, practising engineers, existing products, and engineering handbooks.

During both semesters, each group maintains a web page to archive information related to its project; these web pages can be accessed at: ⟨http://www.ie.psu.edu/imeinc/⟩. The web pages include photographs of prototypes and the final product, CAD and MasterCAM files, product bills of materials, cost estimates, vendor contact information, and presentation slides. The web pages serve also as an archive of past projects and a source of ideas for future projects.

Evaluation of student performance is based on three elements: (1) regularly scheduled design reviews, (2) final project presentations, and (3) the students' design notebooks. The *design reviews* occur 4–5 times each semester following the completion of each of the major tasks outlined earlier. Each team makes a brief computer-based presentation about their recent activities, and this is immediately followed by an in-depth critical question-and-answer session. The faculty serve as reviewers; they seek to establish the capabilities and limitations of each design, help the students to anticipate future problems, and provide verbal feedback on the quality of their work. A written review of team performance is provided after each design review. The written review includes a numerical score on various attributes and specific comments on the particular design. Attributes were selected from the scoring scale for team-based design developed by Trevisan *et al.* [11], and an example is shown in Table 1. A student team is given two numbers for each category: (1) an assessment of team performance in that category, and (2) the faculty expectation at that point in the design process. For example, early in the design process a group might be assigned a rating of 3 on evaluation and decision-making, and the faculty expectation could also be 3, indicating that this team is exhibiting good performance on that metric at that point in the design process.

A *design notebook* is developed and maintained by each student throughout the course. Students record notes from team meetings, concepts, design sketches, production plans, prototype and test results, schedule changes, etc. A notebook with bound pages is required, and each entry must be dated. The notebooks are collected and examined by the faculty after each design review. The design notebook provides a record of each student's contribution to the team and is currently the sole means of individual student evaluation employed in the course. Criteria for evaluating the notebooks include presence of required elements (e.g. dates, contact information for team members, etc.),

Table 1. Sample of scoring scale for team-based design

CATEGORY: DESIGN PROCESS				
Subcategory: Evaluation and Decision-Making				
1	2	3	4	5
Only cursory analysis of ideas; decisions made arbitrarily		Analysis limited in perspectives considered; numerical analysis of uncertain reliability		Quantitative and qualitative issues analyzed; appropriate analytical and experimental methods, tools, and information used; decisions based on established criteria

clarity of sketches, completeness of notes, and quantity and quality of the student's original contributions in support of the project. At the end of each semester, *final project presentations* are scheduled, which are similar in style to final presentations in our other design courses. Interested faculty and students not directly involved with the course are invited to attend the final project presentations.

In addition to providing practical hands-on experience in product realization, IME Inc. is also unique in that it is designed to promote lifelong learning. This latter objective is motivated in large part by ABET's Engineering Criteria 2000 [12], which places considerable emphasis on lifelong learning in engineering education. IME Inc. challenges students to seek out and assimilate information necessary to support their design and manufacturing process development. To assess the impact of IME Inc. on students' lifelong learning abilities, we employ the Self-Directed Learning Readiness Scale (SDLRS) to assess students' lifelong learning abilities [13]. The SDLRS is a self-report questionnaire designed to 'gather data on learning preferences and attitudes toward learning' [14]. The SDLRS has been used in more than 3000 cases in the United States and Canada, as well as a number of other countries [15]; however, it has found limited use in engineering thus far. The SDLRS is administered and scored anonymously at the beginning and end of IME Inc. to evaluate the impact of the educational activities on a student's learning readiness (i.e. comfort with and motivation for learning how to learn).

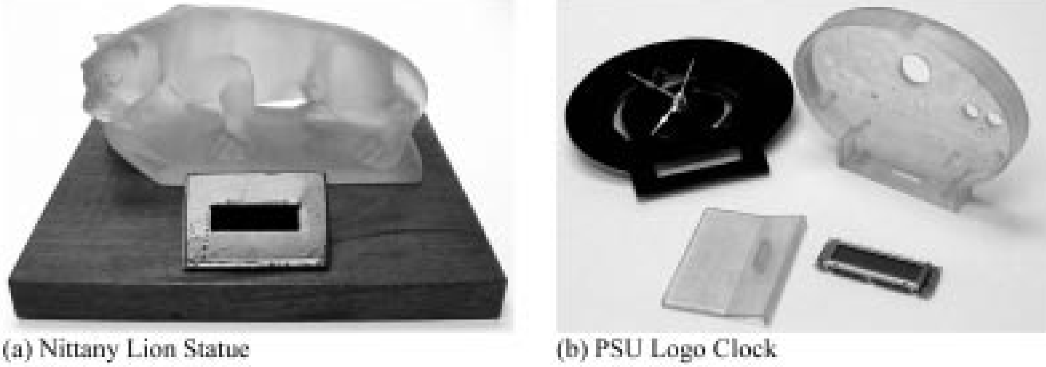
FACILITIES

In order to achieve the course objectives, it is necessary that students have access to facilities for designing, prototyping, and manufacturing products. IME Inc. was structured to utilize several laboratories in the Industrial and Manufacturing Engineering Department, including CAD/CAM, rapid prototyping, electronic assembly, and the Facility for Advanced Manufacturing Education (FAME). The CAD/CAM laboratory consists of engineering workstations running Pro/Engineer and MasterCAM. The rapid prototyping laboratory contains a 3D Systems stereolithography machine and facilities for making silicone rubber molds. The electronics assembly laboratory contains equipment for populating and soldering printed circuit boards, including a screen printer for applying solder paste, a programmable component insertion machine, stations for manual component placement and soldering, an infrared reflow oven, a vapor phase machine, and a wave soldering machine. The 10,000 square foot FAME lab includes facilities for casting, welding, machining, forming, and injection molding. Twelve CNC machines—six horizontal and six vertical—provide the capability for pilot and final production runs of machined parts. Finally, the College of Engineering also has an Electronic Design Services group, whose mission is to provide design and prototyping services for the college as well as external customers on a fee-for-services basis. IME Inc. utilized this group for design, prototyping, and programming of the LCD assembly, which was then produced in volume in the electronics assembly laboratory.

Together, these laboratories offer a broad range of manufacturing capability, which allow the students significant flexibility in product design. IE students on the teams will have already completed a laboratory course in the FAME lab during which they learn basic safety principles and operation of some of the equipment. Course faculty and department technical staff assist the students in developing their skills with other laboratory equipment as needed. Once they have demonstrated a reasonable level of proficiency, the students are allowed to schedule the lab equipment during times when it is not in use by other courses.

FIRST OFFERING OF IME INC. (SPRING AND FALL 2000)

IME Inc. was offered for the first time in spring and fall 2000. Eleven students and five faculty members participated in the first offering of the course; 10 of the 11 students enrolled in both



(a) Nittany Lion Statue (b) PSU Logo Clock

Fig. 2. IME Inc. prototypes from spring 2000.

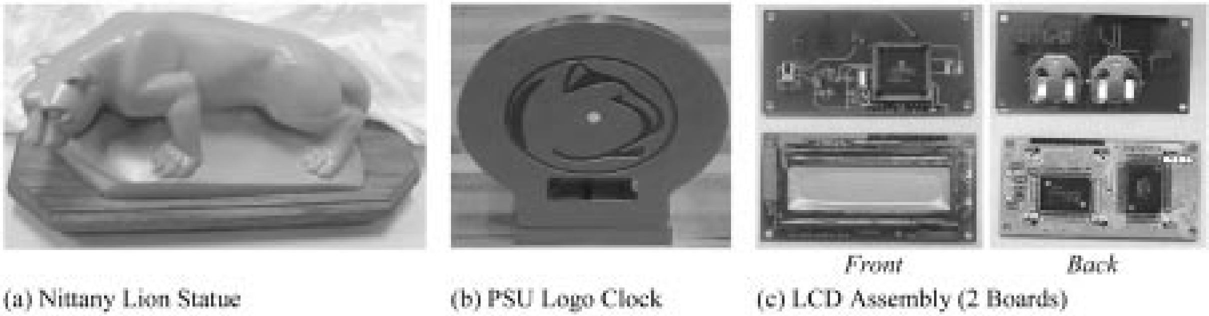


Fig. 3. Final products from IME Inc. in fall 2000.

semesters. The students were instructed to design a product that utilized a programmable LCD assembly. The students were provided with a breadboard prototype of the LCD assembly, programmed to display the Penn State football schedule. The students were divided into groups of 3–4 students, each of which developed several design concepts. After presentation of the design concepts, students and faculty decided to proceed with two products: (1) a Nittany Lion statue with an LCD clock display, and (2) a stand-up analog clock with a Penn State logo and LCD showing Penn State trivia. The students were reorganized into two teams to continue product design and development. By the end of the spring semester, each group had a prototype of their product (see Fig. 2) and a manufacturing plan.

The statue group planned to cast the lion using a silicone rubber mold made from a rapid prototype; mold making and casting would be done in the rapid prototyping laboratory. The base would be cut from wood, and a metal housing for the LCD display would be cut and welded in the FAME lab. The clock group planned to injection mold the face, back, and stand for the clock and purchase a ready-made clock mechanism. Since the injection molding capability in the FAME lab was not sufficient for the size of the components, the faculty began to explore alternatives for obtaining or gaining access to a larger injection molding machine. Two team members from each group were assigned to a third group to work on the final design of the programmable LCD assembly.

The first activity of the second semester was to develop a schedule for finalizing manufacturing methods, obtaining sample materials, conducting a pilot run, ordering production materials, and making the production run. It was at this point that the students began to realize the extent of activities that they would be required to complete in a relatively short period of time. The statue group split into two subgroups, with one group responsible for making the housing and base and the second responsible for manufacturing the lion. The electronics group decided, after consulting with the other groups, to produce a single LCD assembly that could be used in both products, programmed to display Penn State trivia. The clock group proceeded in two directions: (1) planning to machine the clock parts in the FAME facility, and (2) planning for injection molding in conjunction with the Plastics Engineering Technology Department at Penn State Erie.

Because of time and cost overruns, the faculty decided to scale back the production run requirements to 30–40 units each, rather than 100. By the end of the semester, the clock group and statue group had completed their production runs. The electronics group was not able to produce the required quantity, due to delays in obtaining components and failure to verify that the existing solder paste was still usable. Figure 3 shows the final products for each group.

SECOND OFFERING OF IME INC. (SPRING AND FALL 2001)

The second offering of IME Inc. was in spring and fall 2001. Student enrolment jumped to 31 students (22 IE, 4 ME, and 5 EE) in the spring due to (1) word-of-mouth generated by the first course and (2) recruitment of ME and EE students from the senior capstone design courses. In addition, 12 students from the undergraduate honors program in the Smeal College of Business participated in the class along with their instructor. The 12 business students were majoring in marketing, financing, management, and accounting and were assigned the following tasks:

- market research/surveys;
- pricing products for sale;
- estimating market demand;
- operational analysis and business plan to run IME Inc. as a business; and
- developing an e-commerce site for selling IME Inc. products.

The engineering students were divided into six teams, based on their GPA, major, and experience with CAD, CAM, CNC machining, etc. Two business students were then randomly assigned to each team. Each team was tasked with designing and prototyping a product that either had moving parts or used the LCD assembly developed previously. An additional caveat was that most, if not all, of the parts should be capable of being manufactured within the department's facilities.

(a) Replica of Old Main Building (b) PSU Music Box (c) Lawn Ornament

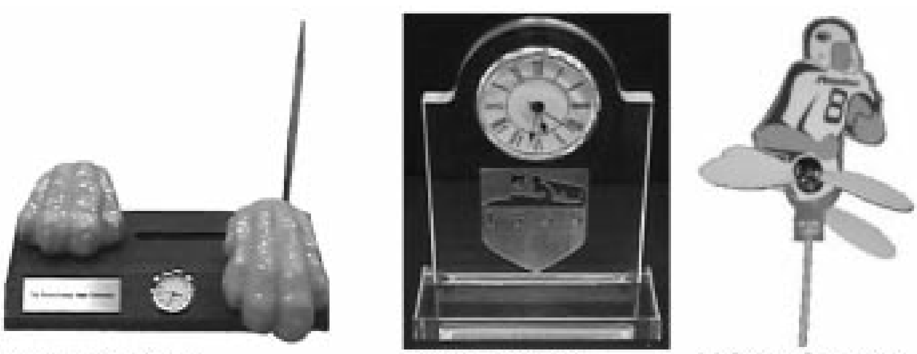
Fig. 4. Some of the prototypes from IME Inc. in spring 2001.

Finally, we also suggested Penn State students and alumni as the initial target market to facilitate market research but encouraged them to think beyond the university.

After considerable brainstorming and market research, the groups settled on the following six products: (1) a desk set with replicas of the Nittany Lion paws, (2) an acrylic clock with a PSU logo, (3) a Nittany Lion coin bank, (4) a music box with a rotating PSU football, (5) a replica of the Old Main building at PSU, and (6) a lawn ornament with a running PSU football player. Only the music box and the lion coin bank were designed to use the LCD assembly; the other products contained multiple parts, of which at least one moved. These products were refined over the course of the spring semester through prototyping and periodic design reviews conducted by the faculty. Each group had a working prototype and a manufacturing plan for their product by the end of the semester. With the exception of the coin bank and the desk set, the products were going to be machined in the FAME lab. Meanwhile, the lion coin bank was going to be made from ceramic using a 12-piece mold, and the desk set was going to have a wooden base with the paws cast in gypsum using silicon rubber molds in a manner similar to that used for the lion statue the year before. Prototypes of the Old Main replica, the PSU music box, and the PSU football player lawn ornament are shown in Fig. 4.

In the subsequent fall, enrolment decreased to 22 students, since the ME and EE students graduated in the spring. The Nittany Lion coin bank was also dropped from the product offering because of its complex and difficult molding process. The groups were reorganized into five teams to reflect the decreased product offering, and 10 new business students from the honors program joined the class, two per team, since only five products were being carried into production. Each of the five faculty members became responsible for one group and its product, while the business students reported collectively to their instructor.

The five groups worked independently during the fall semester, refining their designs to decrease their costs and improve their manufacturability. The Old Main replica, for instance, initially weighed 15 lb, cost $60 in materials, and required over seven hours to machine; by the end of the fall semester, the weight was reduced to 8 lb, material costs were decreased to $28, and machining time was only 105 minutes. Several design simplifications were also made to the other products to facilitate production: the music box no longer played music and the 'legs' of the PSU football player on the lawn ornament—compare Fig. 4c to Fig. 5c—were eliminated, because the mechanism



(a) Paws Desk Set (b) Acrylic Clock (c) Lawn Ornament

Fig. 5. Some of the final products from IME Inc. in fall 2001.

Fig. 6. E-commerce site for marketing IME Inc. products.

was deemed 'insufficiently robust'. In reality, the EE and ME students who were responsible for these features had graduated, and the continuing IE students eliminated nearly everything from their designs that they did not feel comfortable making. The final versions of the paws desk set, acrylic clock, and PSU football player lawn ornament are shown in Fig. 5. These three groups achieved their production goal of 50 units, which was lowered from 100, since five products were being manufactured. Only 20 replicas of Old Main were produced, due to time and cost constraints, and about 15 units of the PSU football box were fabricated owing to repeated problems with chatter and tool breakage. The problems occurred from a design change late in the semester which they uncovered too late to fix: the group decided to use tubular stock to save material costs, but they did not realize until they began production in the last week of the semester (despite our best efforts to get them to start earlier) that they needed a better fixture to secure the part during machining.

While the engineering students were manufacturing the products, the business students designed, developed, and implemented an e-commerce site to market and sell them (see Fig. 6). While none of the products were actually sold, development of the e-commerce site provided a valuable experience for the students involved, as well as a good advertising tool for the course. The business students also produced a detailed business plan for running IME Inc. as a corporation and this was presented to their industry advisory board, which consisted of local entrepreneurs and business people who help mentor students in the business school. This business plan has since been developed into an educational CD that is now being used as a teaching tool in other sections of the honors program in the business school. The business plan and e-commerce site can be accessed online ⟨http://www.cshop.com/ba497c/bplan.htm⟩.

ASSESSMENT OF STUDENT LEARNING

Student learning is assessed both quantitatively and qualitatively in IME Inc. The Self-Directed Learning Readiness Scale (SDLRS) described previously is used to quantitatively assess readiness for self-directed learning, while individual learning essays are used for qualitative assessment. Analysis of each from the 2000 and 2001 offerings of IME Inc. follow.

Summaries of the pre-test and post-test SDLRS scores for the 2000 and 2001 offerings of the course are listed in Table 2 and Table 3. In 2000, the mean pre- and post-test scores both fall in the 'above average' range of 227–251, based on nationally normed data. In 2001, the mean pre-test score falls in the 'average' range, while the post-test score falls in the 'above average' range. Statistical analysis of each of the data sets using dependent t-tests showed that the pre-test/post-test differences in means were significant in 2000 and 2001 at the 95% confidence level. The higher post-test means in 2000 and 2001 indicate that many students have improved their readiness for self-directed learning as a result of participation in IME Inc.

Table 3 presents the distribution of scores for the pre- and post-tests. In 2000 and 2001, more than half of the students fell in the 'below average' and 'average' categories based on their pre-test

Table 2. Pre- and post-test results of the SDLRS scores

		Pre-Test Score	Post-Test Score	Change in Score
2000	Mean	228.18	241.55	10.80[a]
	Std Dev	21.89	14.15	21.74
2001	Mean	215.37	227.00	11.63[b]
	Std Dev	12.81	16.24	17.75

[a,b] $p < 0.05$ for dependent t-tests of differences between pre- and post-test means.

Table 3. Learning readiness based on pre- and post-test SDLRS scores

		# Pre-Test Scores in Range		# Post-Test Scores in Range	
Score Range	Learning Readiness	2000	2001	2000	2001
58–176	Low	0	0	0	0
77–201	Below average	1	3	1	2
202–226	Average	4	14	1	5
227–251	Above average	3	2	6	11
252–290	High	2	0	2	1

scores, whereas more than half of the students moved into the 'above average' and 'high' categories based on their post-test scores. In future course offerings, we plan to include testing of control groups to allow a more precise assessment of the impact of IME Inc. on changes in SDLRS scores.

A plot of the changes in SDLRS scores for individual students is shown in Fig. 7. The largest increases tended to occur for students who initially had lower SDLRS scores, as might be expected, since these students had the greatest potential for improvement. A few of the students actually had lower post-test scores. Most of the decreases are small enough that they can be attributed to test-to-test reliability of the instrument; however, one student showed a decrease that is larger than might be expected on this basis. It may be that this particular student had overestimated his/her ability to undertake self-directed learning and, after working with other individuals who were more highly capable, he/she assessed his/her skills more realistically, leading to a lower post-test score. These findings are consistent with trends we have observed in other studies using SDLRS in engineering courses [13].

In addition to the quantitative assessment of student learning using the SDLRS, each student writes a critical evaluation of 'what they learned about product design and manufacturing and how their views of design and manufacturing changed over the course of two semesters'. Given the open-ended nature of the assignment, students discuss a myriad of topics, but analysis of the essays revealed several common themes woven through their writing. Table 4 contains a summary of these common themes and the number of students who wrote about each. Note that 11 and 18 essays were analyzed from the 2000 and 2001 offerings of IME Inc., respectively.

All students in both courses commented on some aspect of design and manufacturing as we requested in the assignment. The majority of the students also remarked on the ways in which working in a group created both productive and challenging *group dynamics* and developed their

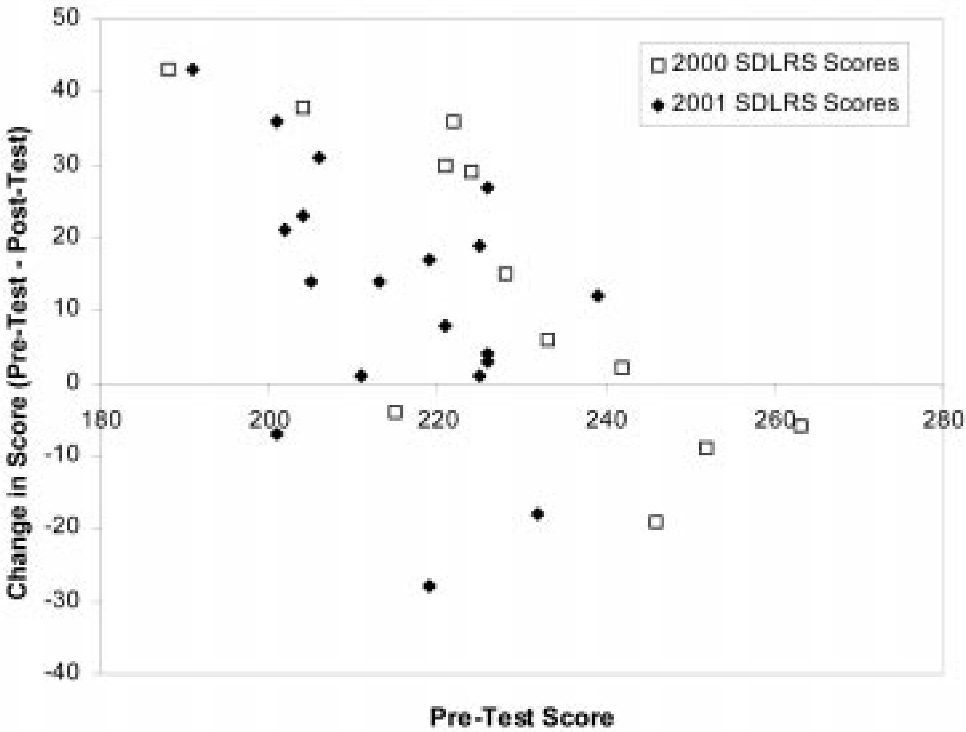


Fig. 7. Change in SDLRS score vs. pre-test score.

Table 4. Common themes in student learning essays from 2000 and 2001

Theme	Number of Respondents 2000 (out of 11)	2001 (out of 18)
Teamwork/Group Dynamics	11	12
Communication	11	13
Design and Redesign	11	15
Manufacturing Skills/Tools	9	18
Time Management Skills	8	9

individual *teamwork* skills. Students learned to trust their teammates to complete their portions of the work and to do the job well. They also saw the benefits of working with people who have skills different from their own. Students enjoyed learning from each other, which they referred to as 'cross-training' from more experienced teammates. Many commented that the amount of work involved in the project necessitated several team members working together.

> *The most valuable thing I take from this class is my experience working with a group. I worked with groups in other classes, but it was just mainly to write reports. In this class it was so much more. I really had to learn how to swallow my pride as many of my ideas where shot down. I also had to learn how to see things through other people's eyes.*

> *I've gained valuable skills while working with my partners. Although I've taken many courses where group work was necessary, it has never been such a partnership for long months on one single project. . . . This is something very valuable to gain from this course, since virtually nowhere before graduating, such collaboration can be achieved.*

On the other hand, a number of engineering students in 2001 complained that the business students failed to attend scheduled meetings and were not contributing members of the group. One student even believed that working with the business students was a 'hindrance'. Still others suggested that the business students' market research findings were inconclusive at best. Interestingly enough, the business students reported the same thing to their instructor about the engineering students: they were 'difficult to reach' and 'they ignored us'. From our viewpoint, it appeared that much of the difficulty was due to each group's lack of understanding of the other group's objectives, expectations, and methods of working. We discuss this more in the next section.

Effective *communication* was considered by many to be vital to completing their products. Students discussed two main types of communication skills and two contexts for communicating, and their comments suggested that they developed or improved both formal and informal communication skills. Formally, teams were required to give presentations throughout the course. Informally, team members needed to be able to discuss their ideas among members of their group and to develop coherent arguments to persuade group members to listen to and adopt particular ideas or concepts. Two students, in particular, were pleased with the improvement they saw in their public speaking skills and their confidence in speaking in front of a group.

The contexts of communication identified by the students included communicating among group members and communicating with others outside the group. Within their teams, some students had difficulty articulating their arguments, while others reported having developed the confidence and skills to 'win' a persuasive argument. Students also wrote about communicating with others outside the group, including vendors, technicians, professors, etc. Students indicated that they thought that practising engineers interact with several parties during the course of a single project and that they improved their communication skills as a result of IME Inc. A few students emphasized the importance of establishing a good relationship with vendors, asking for special requests and discounts, and maintaining consistent contact with vendors and suppliers throughout the course of product manufacturing.

> *When dealing with vendors and consultants, specifications need to be absolutely clear. I have learned more practical lessons from this experience than from any other course I have taken at Penn State.*

> *The thing I am most proud of though is my improvement in public speaking . . . the repetition of giving presentations every few weeks and that I knew what I was talking about, made me feel so much more comfortable in front of everyone.*

Many students also commented on the reiterative processes of *design and redesign* and the *complexities of the design process*. Several students noted that their original design ideas were subject to almost constant redevelopment due to design constraints, material and/or tool unavailability, and financial restrictions. They also acknowledged the ways in which results from market research surveys shaped the redesign of certain aspects of their products. In trying to improve their design or overcome various manufacturing obstacles, students believed they enhanced their problem-solving skills. A number of students cautioned, however, that a time comes to stop redesigning and begin manufacturing. Moreover, individuals mentioned the constraints of budget limitations. This course constituted the first time many students had been required to work within a budget, and they suggested these restrictions forced them to think in imaginative and resourceful ways.

> *. . . learned to consider all options before making a decision and to know when to stop redesigning—no more changes . . . there is a point when you need to 'stop listening,' stop redesign and move on to get things done.*

All of the students commented on the *manufacturing skills and tools* used by their group, including:

Pro/Engineer, MasterCAM, silicone rubber molding, hydro-stone casting, mixing plaster, 'using fixtures to ensure accurate part size and cutting conditions', using CNC mills and lathes, etc. For example, an ME student with little manufacturing experience realized the value of having fixtures after spending many hours preparing parts for machining:

> *I had never had reason to fixture anything before; I didn't know what it even entailed. And I have definitely never participated in mass production. . . . So having to deal with creating a way to keep everything in place run after run after run so that the parts were all the same and lined up correctly was another lesson for me.*

Many students also described the problems and difficulties they encountered during manufacturing: tools broke, supplies arrived late, materials were of poor quality, group members were absent, etc. Students learned that materials and service vary from vendor to vendor and that the quality of vendor service and merchandise affected their manufacturing schedules. By and large, students witnessed the differences between and complexities in making one product prototype versus making multiple copies of a single product.

> *I never realized how much effort and planning went into making a single product.*

> *We learned . . . the process used to make one product does not necessarily follow the process that must be used to make a significant quantity . . . after breaking 2 tools, we realized that our cutting depth was too deep, and the spindle speed was too slow.*

Lastly, in regard to the processes of designing and manufacturing, students mentioned that *time management skills* were very important because of all the 'independent work with given deadlines'. Due to the scope of the project, students found it necessary to budget their time in order to complete subtasks and meet the final project deadline. The degree to which students felt they effectively managed time varied. Some students believed the course allowed individuals and groups to work independently, setting their own sub-goals during the course of the project and improving their time management skills. Others acknowledged that their products would not be completed until after the course deadline (i.e. during finals week).

> *Real-world challenges were present with the complications experienced with the suppliers. The seemingly constant miscommunication and challenges experienced in this aspect exposed all of us to how drastically this can increase lead-time of realizing a product.*

> *I procrastinated a lot because I thought I had all the time in the world. Looking back, however, I wish I did more work in the first part of the course because my workload this semester, specifically in the second half, has really been intense. This experience has taught me that the real world will not tolerate procrastination and that I need to learn to become a self-motivator, even at the grimmest of times.*

In addition to these commonly discussed themes, several students indicated that IME Inc. provided a great opportunity to *apply theories learned in previous courses* and considered the experience a beneficial precursor to their engineering careers. Students thought the overall design of the IME Inc. course encouraged students to be more creative than is allowed in other engineering classes, but they found that *being realistic* about the scope of the project was vital to completing their products. Students also advised production teams to 'devise a plan and stick to it'. Comments along these lines suggested that groups ought to agree on a viable design as soon as possible, without compromising the manufacturability of the product, and to devise and adhere to a feasible schedule for manufacturing the product. Some students believed they took too long to agree on a design or continued redesigning the product too long into the second semester; others had difficulty 'letting go of old ideas'.

> *I was under the impression that a detailed design and production plan would eliminate most of the unforeseen problems or at least prepare you to detect them as soon as possible and fix them. Our group was making so many last minute changes that we had to abandon our original ideas and scramble to fix the problems as they arose. With this technique only came more problems and more quick but poor solutions.*

Several students identified *having a back-up plan* as one of the most valuable lessons learned in IME Inc. Broken tools, inconsistency in the quality of materials, lack of equipment ideally suited to the project, and other challenges forced students to generate alternative plans for finishing their products on time. While each group seemed to cope with obstacles, all suggested that back-up plans should exist even before something goes wrong.

> *The number one lesson learned was that problems will happen. For instance, vendors will be late or send defected* [sic] *parts, parts will be out of stock, machines will break, and deadlines will creep up.*

Finally, a few students noted that *asking questions and seeking advice* from faculty and peers was also helpful in redesigning and manufacturing their products. They mentioned specific examples of problems solved by seeking advice from others, an important part of becoming a more proficient self-directed learner.

CLOSING REMARKS

As with any new course many things went well and as expected, but many other things did not. Having heard from the students in the previous section, we would like to close by sharing some of what we, the faculty, learned, in order to summarize the benefits and drawbacks of offering such a course.

What went right

Overall, the students' essays indicated a great deal of satisfaction with the IME Inc. course and the degree to which it prepared them for their engineering careers. They enjoyed seeing an idea come to fruition and gained first-hand experience in the entire product realization process. They benefited from the 'real-world' and 'hands-on' aspects of the course and found out what it was like to work with vendors and suppliers outside the university. They further developed many of the 'people skills' that frequently receive little attention in engineering courses: teamwork, communication, and decision-making; nearly every student commented on the importance of effective communication and teamwork in the learning essays.

In addition to the many direct benefits of the course, students also found many indirect benefits from taking the course. Many of the students acknowledged that IME Inc. made for great conversation during job interviews and that the breadth and depth of their experience in the course impressed many interviewers. Several students even carried prototypes to their interviews. Many students also found that IME Inc. reinforced their learning in other courses, and we hope to see more cross-fertilization as more products are developed and produced in IME Inc. The course has already begun to serve as a 'living factory', generating case studies and examples for other courses within the department. For instance, students in IE466 (Concurrent Engineering) have helped develop new product concepts for IME Inc., while students in IE464 (Assembly of Printed Circuit Boards) have fabricated parts for the LCD prototype.

What went wrong

Perhaps the biggest drawback to IME Inc. was the open-ended nature of the course. The general charge given to students provides few constraints on the design concepts they generate. Students also have had difficulty understanding the product design and development process, complaining about the 'lack of direction' in the course. In 2000, several students reported that course guidelines and faculty expectations were not as clear as they would have liked:

> *The course was vague and unstructured. I was confused on what was expected of us, and what goals were trying to be reached.*

In 2001, we started adopting a more structured approach to the course. In particular, we now use Ulrich and Eppinger's [16] *Product Design and Development* text to provide a more detailed roadmap through the product realization process. Clearly defined milestones are now regularly scheduled, along with specific deliverables, but faculty expectations are still evolving.

The design reviews throughout the course were successful in keeping groups on track; however, we found that they must be carefully managed in order to maintain a positive atmosphere and not discourage students. We learned that more frequent design reviews were needed, in addition to more prototyping and testing. A considerable amount of redesign still occurs in the second semester of the course as the students begin testing their products and trying to manufacture them. We have increased the number of design reviews and specified the content of each review. We have also started requiring an appearance prototype approximately halfway through the first semester and a functional prototype by the end of the first semester. These changes have alleviated some of the redesign in the second half of IME Inc., allowing more time for fine-tuning the manufacturing process, but students continue to push the final delivery deadline.

The interactions with the business students had benefits as well as drawbacks. Many engineering students suggested abandoning the interactions with the business students because they added little value to the team, while others suggested coordinating class times better to ensure all parties can attend scheduled meetings. Part of the difficulty stems from when the business students get involved in the process. It is difficult for them to market a concept before it has been prototyped, and it is difficult for the engineering students to develop cost estimates for the business students when the concept is constantly being refined. In the most recent offering of IME Inc., these communication difficulties have been alleviated by clearly defining the responsibilities for the engineers and the business students, as well as their expectations for each other. The engineers and the business students also work more closely together during the second semester of IME Inc. when a working prototype is available. This gives the business students a physical prototype to conduct market research with local businesses and to use to estimate production costs. The engineering–business student interactions are much improved as a result.

Finally, as we look further into the future, we recognize that the course will continue to grow in size, as will the number of products being developed. Some students have suggested reducing the number of products and consolidating groups, but groups with more than five or six students do not work well: meetings are difficult to coordinate and some people 'coast'. We also recognize that the course requires a significant investment of faculty time as it is currently structured. We are now in the process of developing methods that allow us to offer the course to a larger population of students while keeping faculty commitments at a reasonable level.

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