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

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Abstract

IME, Inc. is a new two-semester undergraduate course in which multidisciplinary student teams first design and prototype new products, and then produce them in volume. The objective in the course is to provide students with manufacturing and production experiences analogous to those obtained by an English student working on a student-run newspaper. The course integrates the traditional capstone design experience with hands-on experience in volume production and manufacturing; students must consider all aspects of manufacturing – including process planning, tooling, assembly, outsourcing, and final costs – so that they can produce approximately 100 units using the new *Factory for Advanced Manufacturing Education.* The course also focuses on creating an environment that promotes self-directed learning, problem solving, teamwork, project planning, communication, and presentation skills. Assessment strategies for evaluating team performance and the impact on students' learning readiness are discussed. 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. Finally, plans for using *IME, Inc.* as a "living factory" and involving students from other majors (e.g., business and information technology) are also discussed.

I. Introduction and Motivation

English majors can run their own newspaper, communication majors can produce their own television or radio shows, and business majors can create their own business plans, but where can engineering students, interested in design and manufacture, design and produce their own products? 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 industry. Senior capstone design courses and student projects like SAE Formula Car or Hybrid Electric Vehicle have been created to provide engineering students with "real world" and "hands-on" design experiences. For instance, Shah, et al.[1] describe a virtual corporation designed to simulate real world collaborative design and build a product from scratch. Similarly, 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.[2] The product being realized in facilities like these and in student design projects, however, is often only a prototype. Rarely will students 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*. Such is the impetus for *IME, Inc.*, a new two-semester undergraduate course in which multidisciplinary student teams design 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 using the new *Factory for Advanced Manufacturing Education*. As such *IME, Inc.* integrates the traditional capstone design experience with hands-on experience in volume production and manufacturing. The course is jointly taught by five faculty with expertise in: product design, CAD/CAM, rapid prototyping, plastic injection molding, electronic assembly, and manufacturing systems design.

In addition to providing practical hands-on experience in product realization to help engineers better satisfy industry expectations,[3] *IME, Inc.* is also designed to promote lifelong learning. The latter objective is motivated in large part by ABET's Engineering Criteria 2000,[4] which places considerable emphasis on lifelong learning in engineering education. *IME, Inc.* challenges students to seek out and assimilate the information needed to support their design and manufacturing process development. To assess the impact of *IME, Inc.* on students' lifelong learning abilities, we are using the Self-Directed Learning Readiness Scale (SDLRS) to assess students' lifelong learning abilities.[5] The SDLRS is a self-report questionnaire designed to "gather data on learning preferences and attitudes toward learning".[6] The SDLRS has been used in more than 3000 cases in the United States and Canada, as well as a number of other countries;[7] 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). Analysis of the preliminary results is discussed in Section VI. Meanwhile, a description of *IME, Inc.* is given in the next section followed by an overview of our production facilities in Section III. Our experiences with the first offering of *IME, Inc.* are discussed in Section IV, and a summary of what went right and what went wrong is given in Section VI along with future course modifications.

II. Course Description

The primary objective in *IME, Inc.* is to provide an integrative, hands-on experience in all of the elements of the product realization 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 targeted at junior year IE, EE, and ME undergraduates, both to provide them with a significant engineering design experience early in their major course sequence and to engage their interest in other courses that feature formal instruction in the processes and techniques that they are introduced in the course.

IME, Inc. is delivered as a two-semester sequence. The first course covers product design while the second focuses on manufacturing process design and production. In the first course, students are given a very general charge (e.g., develop a product that utilizes a programmable LCD assembly and is marketable). The students work in 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 estimates, and
- create an initial manufacturing process plan.

During the second course, students implement the 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, and
- conduct a production run of approximately 100 items.

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. Lecture time is minimal, taking the form of workshops on specific tools or methods (e.g., brainstorming techniques, Pro/Engineer, MasterCAM) presented 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 resources such as the faculty and technical staff, web sites, practicing engineers, and engineering handbooks.

During both courses, each project team maintains a web page to archive information related to their project.[8] The web page includes items such as photos of prototypes and the final product, CAD files, presentation slides, and product bills of materials. 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 after completion of each of the major tasks. Each team makes a brief computer-based presentation of their activities and results on the task, 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 Davis, et al.,[9] and an example is shown in Table 1. A student team is given two numbers for each category: (1) an assessment of team performance on 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.

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.

A *design notebook* is developed and maintained by each student during 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 is dated. The notebooks are collected and examined by the faculty immediately following 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 (dates, contact information for team members), 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.

III. 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 & Manufacturing Engineering Department, including CAD/CAM, rapid prototyping, electronic assembly, and the *Facility for Advanced Manufacturing Education* (FAME). Together, these laboratories offer a broad range of manufacturing capability, which allows 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 work with the student groups to develop 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.
The CAD/CAM laboratory consists of engineering workstations running Pro/Engineer and MasterCAM. The rapid prototyping laboratory contains a 3D Systems stereolithography machine (Figure 1), and facilities for making silicone rubber molds (Figure 2). The electronics assembly laboratory (Figure 3) 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 (Figure 4) includes facilities for casting, welding, machining, forming, and injection molding. Twelve CNC machines (Figure 5) provide the capability for pilot and final production runs of machined parts.

Figure 1. Stereolithography Machine

Figure 2. Vacuum Chamber for Molds

Figure 3. Electronics Assembly Laboratory

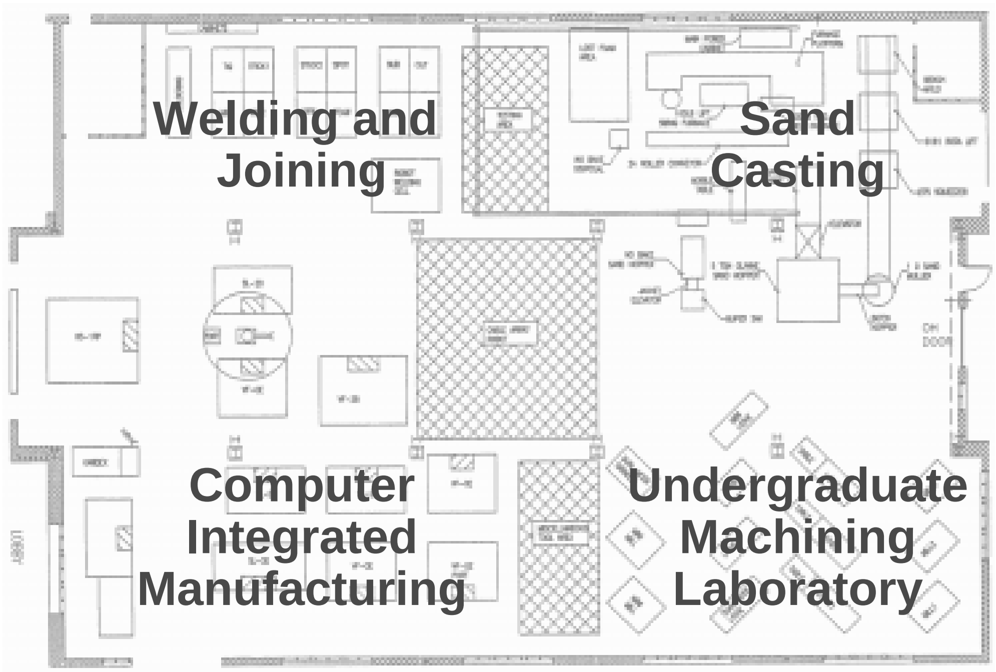


Figure 4. Layout of FAME Laboratory

Figure 5. CNC Machines

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.

IV. Experience with the First Offering of *IME, Inc.*

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 eleven enrolled for both semesters. The students were directed 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 teams, 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 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 (Figures 6 and 7) and a manufacturing plan.

Figure 6. Statue Prototype

Figure 7. Clock Prototype

The statue group planned to cast the lion using a silicone 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 final design of the programmable LCD assembly.

The first activity of the second (Fall) 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 one short semester. 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 along two directions: (1) planning for injection molding, in conjunction with the *Plastics Engineering Technology Department* at Penn State Erie, and (2) planning to machine the clock components in the FAME laboratory.

During the second semester, the students began to realize many of the difficulties associated with manufacturing a product. Some of these difficulties are described below, and illustrated with examples from the course.

- *Designs that had been assumed to be final required significant revision.* After creating several prototypes, the statue base group came to realize that their design was impractical from a manufacturing time and cost viewpoint and began development of a new base that eliminated the LCD assembly.
- *Manufacturing processes were not as easily mastered as expected.* The statue group spent significant time experimenting with methods for making molds, different casting materials, and methods for eliminating air bubbles from the final casting.
- *Working with vendors and contractors created delays and other difficulties.* The electronics group had difficulty obtaining the needed components due to a national shortage, had to return a solder paste screen because of incomplete specifications on the purchase order, and were frustrated by contractor delays in board design, programming, and test.
- *Manufacturing time needed to be significantly reduced.* The clock group had to make several design changes so that the product would be suitable for machining, consult with a vendor who helped them design a custom fixture, and conduct extensive experimentation with machining parameters in order to reduce machining time sufficiently to make the production run feasible while maintaining part quality.

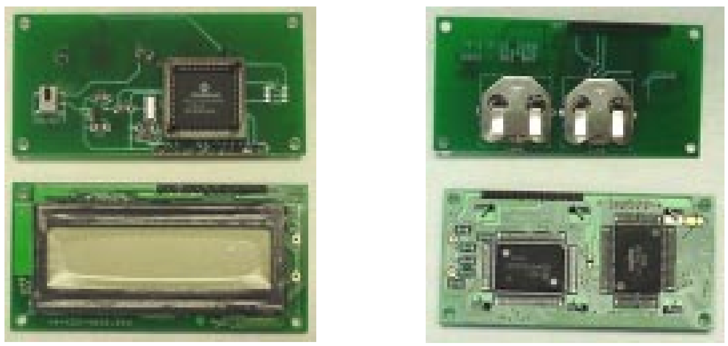
Because of time and cost overruns, the faculty decided to scale back the production run requirements to 30-40 units each, rather than 100. By the end of the semester, the clock group and statue group had completed their production runs. The electronics group was not able to produce the required quantity due to delays in obtaining components and failure to check that the existing solder paste was still useable; they agreed to finish board assembly and test at the beginning of the following semester. Figures 8-10 show the final products for each group.

V. Assessment of Student Learning

To assess individual student learning in the course, the SDLRS instrument described in Section I was administered twice in the course: (1) as a pre-test at the beginning of the first semester and (2) as a post-test after the second semester of *IME, Inc.* A summary of the pre-test and post-test scores are listed in Table 1. The average pre- and post-test scores both fall in the "above average" range of 227-251 as designated by the designers of the instrument, with nearly half of the students falling in the "average" or "below average" categories as shown in Table 2. The higher mean and smaller standard deviation in the post-test results indicate that many students can improve their learning readiness by engaging in self-directed learning activities like *IME, Inc.* As shown in Table 2, the number of post-test scores in the “average” or “below average” categories has dropped to 20% with 60% of the scores falling in the “above average” range compared to only 30% previously.

Figure 8. Lion Statue

Figure 9. Clock Housing



(a) Front View (b) Back View

Figure 10. Programmable LCD Assembly (2 boards)

Table 1. Pre- and Post-Test Results of SDLRS Scores

	Pre-Test Score	Post-Test Score	Change in Score: Pre-test – post-test	Change in Score: as a % of Pre-test
Average	228.18	241.55	10.80	5.36%
Std dev	21.89	14.15	21.74	10.22%

Table 2. Pre- and Post-Test Results of SDLRS Scores

Score Range	Learning Readiness	# Pre-Test Scores in Range	# Post-Test Scores in Range
58-176	Low	0	0
177-201	Below Average	1	1
202-226	Average	4	1
227-251	Above Average	3	6
252-290	High	2	2

Subsequent analysis of each of the data sets with the Bonferroni test showed that the pre-test/post-test differences for *IME, Inc*. approached significance but were not significant at the 0.05 level. The lack of significance is very likely influenced by the very small sample size (10) and is expected to be improved by adding additional students to the pool in future studies. Follow-on studies will include testing of control groups to allow a more precise assessment of the impact of *IME, Inc.* on changes in SDLRS scores.

Finally, a plot of the change in SDLRS score as a percent of the pre-test score is shown in Figure 11. Note that some of the largest changes occur for students who initially had lower SDLRS scores while some of the higher scores actually decreased when comparing the post-test and the pre-test scores. It appears that many students tend to "re-center" their scores after working with other individuals who are highly capable self-directed learning.[5] Students who initially "under-score" themselves tend to have large gains in the post-test while students who initially rated themselves high in their ability to do self-directed learning tend to "re-center" and lower their scores during the post-test.

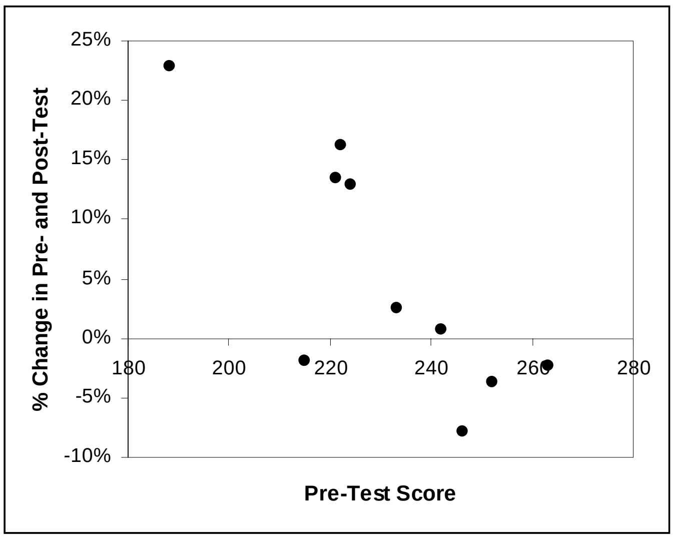


Figure 11. Change in SDLRS Score as a % of Pre-Test Score

In addition to the SDLRS assessment of learning readiness, students were also asked to write a critical evaluation of their learning upon completion of the course. Comments from their individual learning essays yielded insight into the students' learning during the course. For instance, the students learned many valuable lessons about the product realization process:

> "Through experience of this class, leaving out either steps or details in this process of design in order to reduce lead time can hurt the results. It can lead to an inferior product or actually increase the actual time the product will be realized."

> "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 groups

were 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."

Many students alluded to the importance of planning and flexibility as they learned how to deal with ambiguous and open-ended problems:

> "The most important thing that I think I've gained from this class is to understand the importance of planning ahead, and listening to advise from credible sources."

> "The number one lesson learned was that problems <u>will</u> 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. All these things will happen and as an engineer one needs to be flexible to accommodate these problems."

On a more practical note, a mechanical engineering student with little manufacturing experience understood the value of fixturing after spending countless 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 I really had nothing to go on as far as past experience. 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 commented on the "real world" experience of the course. Two students made the following statements in their final learning essays:

> "I have learned more in this class in two semesters than I learned in my other three years at Penn State. It wasn't so much as the book learning, but it was real world learning."

> "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."

The same mechanical engineering student that learned about fixturing also had the following insight about the practical nature of the course:

> "I think that this course should be stressed more as a potential learning experience for ME and EE majors for whom manufacturing is just considered to be something that happens with your design after you're done with it."

Many of the students had never worked with vendors or suppliers before and quickly realized the importance of effective communication when dealing with people outside of the university:

> "Communication is absolutely critical at all stages of the product development process. 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. When dealing with vendors and consultants, specifications need to be absolutely clear. I think I have learned more practical lessons from this experience than from any other course I have taken at Penn State."

The students also learned how communication can strengthen or hinder a team:

> "Communication was the biggest obstruction to the effective workings of the group throughout the design process as an entire group."

Furthermore, very few students get the opportunity to work so closely with the same group of students for two semesters even though many courses now employ group projects. Upon completion of *IME, Inc.*, one student wrote:

> "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."

Another student also mentioned the importance of compromises and the need to appreciate other people's ideas:

> "In working on a daily basis with the members of my design team, I learned that it is not easy to combine the visions of five into a single product. I came to the realization that sometimes you have to let go of your idea of the 'perfect' product and compromise on a common goal. I think that this was one of the hardest parts about the course."

This comment was made by a student who worked "much better as a leader" after realizing that "nothing would have gotten accomplished with five leaders and no one to follow"—a source of much tension in the group during the first semester of the course. Finally, the two comments that best captured the course objectives for *IME, Inc.* were:

> "Overall the complete manufacturing cycle and implementation of a product involves more operations and is more complicated than originally thought in my mind."

> "I came to realize that dreaming about a product and actually making it are two totally different things."

A third student commented that, "You get the satisfaction of seeing your idea turned into a product which everybody wants." So despite the many late nights designing and the countless hours manufacturing, all of the students left with a better understanding of the product realization process and an appreciation for *volume* production.

VI. Closing Remarks

As with most new courses, as many things went right as they did wrong. In closing, we would like to share some of what we, the faculty, learned to summarize the benefits and drawbacks of such a course.

<u>What Went Right</u>

As evidenced by many of the comments in the previous section, the students took a lot away from the course as we had hoped. 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 also liked the industry speakers. They further developed many of the "people skills" that frequently receive little attention in engineering courses: teamwork, communication, and making compromises; nearly every student commented on the importance of effective communication and teamwork in the individual 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. Many students also found that *IME, Inc.* helped them in their other courses; one student commented in his final learning essay:

> "The most important thing that I got from this class was how to apply the many things that I've learned in the last couple semesters. I also got to use some of the things I learned in [Production Engineering] as I had to come up with a process plan and how to fixture the part in the jig so that all degrees of freedom were restrained. I also applied some of the principles learned in [Manufacturing Systems Engineering] and how to make our process more efficient by possibly redesigning where the machines are located in the shop."

We hope to see more cross-fertilization like this as more and more products are developed and produced in *IME, Inc.* As a result, *IME, Inc.* has begun to serve as a "living factory," generating case studies and examples for other courses within the department. For instance, students in *Concurrent Engineering* last fall helped develop new product concepts for the 2001 offering of *IME, Inc.* while students in *Assembly of Printed Circuit Boards* are analyzing and fabricating parts of the new LCD prototype this spring.

<u>What Went Wrong</u>

Perhaps the biggest drawback to *IME, Inc.* was the open-ended nature of the course. The general charge given to students (i.e., develop a product that utilizes a programmable LCD assembly and is marketable) provided few constraints on the design concepts they generated. Students also had difficulty understanding the product design and development process, complaining about the "lack of direction" in the course. We are adopting a more structured approach during the next offering of *IME, Inc.* We are using Ulrich and Eppinger's <u>Product Design and Development</u> text[10] to provide a more detailed roadmap through the product realization process.

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 found that more frequent design reviews were needed in addition to more prototyping and testing. A considerable amount of redesign occurred in the second semester of the course as the students began testing their products and trying to manufacture them. For the next offering of *IME, Inc.* we have increased the number of design reviews and specified the content of each review with reference to appropriate chapters in the text. We are requiring an appearance prototype approximately halfway through the first semester and a functional prototype by the end of the first semester. We hope these changes will alleviate much of the redesign in the second half of *IME, Inc.*, allowing more time for fine tuning the manufacturing and production process.

We also realized that we needed to emphasize more marketing and customer needs analysis during the first half of the semester so that the students can learn how to integrate customer feedback into product development. Toward this end, *IME, Inc.* is providing unique opportunities for collaboration with other majors at Penn State. In particular, during the next iteration of *IME, Inc.* a group of business students in the Honors program will work closely with the students in *IME, Inc.* to develop a business plan for the new product and help with marketing. Thus, the business students will have the opportunity to develop a business plan for a real product that is being manufactured while the engineering students will be exposed to many of the business aspects of developing a new product. We also plan to begin working with the e-Incubator Laboratory, which is part of Penn State's new e-Business Research Center.[11] Our goal is to explore e-business models for a web-based ordering system for the products developed and produced in *IME, Inc.* with the long-term objective of implementing a system through which customers can place orders.

Finally, as we look further into the future, we recognize that the course will grow in size (for the 2001 offering of *IME, Inc.*, 31 students are enrolled and seven products are being developed). We also recognize that the course requires a significant investment of faculty time. We must develop 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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