Experiences in Designing a
Design for Manufacturing (DFM) Course

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Abstract

Mechanical Engineering and Industrial Engineering faculty at The University of Iowa agreed to implement a required undergraduate course for each curriculum that will give students an understanding of basic design principles and manufacturing processes. The new course is called, Design for Manufacturing (DFM). The course goals include giving students the opportunity to develop an understanding of the fundamentals of design, engineering graphics, and manufacturing processes. Topics covered include introduction to design, manufacturing, and design for manufacturing; phases of a product life cycle; product design process; introduction to engineering drawing standards and graphics; computer-aided design (CAD) modeling; and various manufacturing processes. The course includes "hands-on" CAD/CAM and computer numeric control (CNC) machining projects.

This paper discusses experiences in designing and delivering the DFM course. Among the issues that had to be resolved were what topics should be included; what book or books should be used; what software should be used; what kind of laboratory experience should be included; and what resource materials should be chosen for the course?

I.   Introduction

The College of Engineering at The University of Iowa has had a Manufacturing Processes course for more than forty years. The course was originally developed and taught in the Mechanical Engineering (ME) Department, but through a reorganization of the College, the course was transferred to the Industrial Engineering (IE) Department. In the spring of 2002, the two departments were joined into one, the Mechanical and Industrial Engineering (MIE) Department. One of the early faculty actions in the new Department was to create a new course, Design for Manufacturing (DFM), that would be a required course for both ME and IE undergraduates. The course was intended to replace the Manufacturing Processes course required for IE's. The plan was to offer the new DFM course in Spring 2004.

Product design and manufacturing topics were also covered in another IE course called Manufacturing Systems. Initially, the primary emphasis for this course was CAD/CAM methods and 3D solids modeling. The CAD product, Pro/ENGINEER®, was used to give the students hands-on laboratory experience. Each student designed a rotational part and machined it on the Department's CNC lathe. In 2002, the Manufacturing Systems course focus was changed to include contemporary manufacturing and production system topics, and it was believed CAD/CAM topics more logically fit into the new DFM course. To appreciate CAD/CAM fully, it was believed that the DFM course should also contain lectures on engineering graphics, which

is the standard language for communicating designs in industry. Engineering graphics had been taught to freshmen as part of an introduction to engineering course, but was discontinued when the new engineering curriculum was introduced in the fall 2002 semester.

The plan for the new DFM course was that it would include the topics: manufacturing processes, product design fundamentals, engineering graphics, and CAD/CAM. For "hands-on" exposure, CAD, CAM, and CNC laboratory exercises would be included. This 3 semester-hour course for sophomore and junior engineering students would replace the Manufacturing Processes and Manufacturing Systems courses. Since these topics are often covered in two to three separate courses, the development plan was ambitious.

II. Course Development

Courses titled "Design for Manufacturing" exist at other universities including Massachusetts Institute of Technology[1], The University of Pittsburgh[2], Penn State[3], Stanford University[4], the University of Texas[5], and The University of Michigan[6], to name a few. Their course objectives contain a common theme and the blend of topics overlap, but the emphasis on specific topics and course delivery differs.

Industry has long recognized the need to improve communication between design and manufacturing. An industry-driven effort by the Society of Manufacturing Engineers (SME) has encouraged improving manufacturing education through its Manufacturing Execution Plan (MEP)[7]. MEP identified what it called "competency gaps" in engineering education. The 1999 SME report identified many needs, including the need for additional education on computer-aided design software skills, blueprint reading, manufacturing processes, teamwork, and oral and written communication. Although SME/MEP funding was not pursued while developing this DFM course, its documents were reviewed to help validate course topics.

As originally conceived, the course included the following topics: introduction to design, manufacturing, and design for manufacturing; phases of a product life cycle; product design process; introduction to engineering drawing standards and graphics; 3D, CAD modeling; graphical projections; sectional views; dimensioning and tolerancing; mechanical and physical properties of materials; metal, polymer and electronic processing; and integration of design, manufacturing and environmental considerations.

How should the course be developed? Course development works best when faculty who might teach the course are involved. The University wanted one section taught by IE faculty and one by ME faculty. Manufacturing is often not perceived by engineering students and faculty as the most exciting course area, especially when compared with other engineering opportunities. Additionally, in research-based universities, courses that contain continuous learning of CAD/CAM software products are less desirable to teach than more traditional topics such as statics, statistics, and calculus. Further, since CAD/CAM software changes almost yearly, faculty not dedicated to the area find it hard to keep up with the changes. Having someone who has worked in the manufacturing industry and can bring practical experience into the classroom would be best, which often limits the use of junior faculty. On the other hand, senior faculty are often less interested in learning advanced software products.

Dr. Jerz, who had been teaching the Manufacturing Processes course at The University of Iowa as an adjunct professor and at his own university, St. Ambrose University, was asked to help design the new DFM course and to teach the course until University of Iowa faculty could take it over. Dr. Jerz was also teaching Engineering Graphics and Computer-Aided Design at St. Ambrose University.

What software should be used? The College of Engineering currently supports Pro/ENGINEER® Wildfire (Pro/E). While Pro/E is a high-level CAD software package, with a manufacturing module and used by many of our constituencies, it is very time-intensive to learn. Other easier to use products, such as SolidWorks®, are available but the College was not interested in supporting additional CAD/CAM software products. The College owned three copies of Mastercam® software, and Dr. Jerz was using SolidWorks® and Surfcam® at St. Ambrose University. It was decided initially to use Pro/E and Mastercam® and reassess the software issue after the course was delivered.

What textbook should be used? Determining the textbook, or textbooks, to use presented another challenge. The three main topical areas: manufacturing processes, engineering graphics, and CAD/CAM, are typically covered in separate textbooks. CAD and CAM textbooks usually focus the individual topics, but not both. Students typically do not appreciate having to purchase three textbooks. Additionally, the textbook material must closely parallel the CAD/CAM software selected. To avoid having to require three textbooks, development of supporting materials for the course seemed necessary. It was decided to use the manufacturing technology book written by Kalpakjian and Schmid[8], and the Pro/E book written by Toogood and Zecher[9]. The Pro/E book was selected because the projects in it were well suited for manufacturing. CAM topics were to be developed by the instructor.

What kind of laboratory experience should be included? Students best learn how to use CAD/CAM software by completing a carefully planned sequence of laboratory exercises and hands-on involvement with manufacturing processes. This experience can be supplemented with videotapes and demonstrations, but students most remember experiences in which they directly participate. The MIE Department decided to purchase a Techno desktop milling machine for milling, and also planned to purchase a Techno lathe for turning.

III. Course Delivery

In fall 2003, changes were made to the last Manufacturing Processes course offering to introduce several new topics that were to be included in the DFM course. The first official offering of the DFM course was spring 2004.

The course syllabus has evolved through two offerings to include the following statements:

> *This course gives students the opportunity to develop and demonstrate an understanding of product design, engineering graphics, and manufacturing processes fundamentals. The learning objectives are:*
> * *Students will gain an understanding of the major manufacturing processes, including machining, casting, forming, assembly, surface treatment, plastics processing, and inspection.*

- *Students will gain an understanding of engineering graphics and how designs are created and communicated in industry.*
- *Students will learn 3D computer modeling with Pro/ENGINEER® and can create models of relatively complex parts and assemblies, and produce detailed engineering drawings.*
- *Students will develop numeric control programs and machine parts. They will use CAD/CAM software to create designs and manufacture products.*
- *Students will learn about inspection techniques and how to dimension and measure parts.*
- *Students will experience the interactions between product design, material selection, manufacturing process selection, and cost and time tradeoffs.*

Additionally, course goals were associated with the IE ABET Program Outcomes[10], as shown in Table 1.

Table 1. Course Goals and ABET Outcomes

Course Goals	ABET Outcomes[1]
1. Understand the basics of manufacturing processes including machining, casting, forming, welding, plastics, and assembly. Ability to calculate cycle time for some manufacturing operations.	a (●), d (○), e (○), j (○)
2. Develop the ability to use computer-aided design (CAD) software and create part models, assemblies, and drawings.	a (●), c (●) , g (○), i(○), k (●)
3. Understand CAD/CAM technologies and ability to create physical parts.	a (●), c (●) , i (○), k (●)
4. Understanding of engineering graphics principles and how designs are communicated in industry.	a (●) , c (○), e (○), g (●), h (○), i (○), j (○), k (●)
5. Understand the relationships between customer desires, project materials, product design, and manufacturing process selection. Understand product design and manufacturing process tradeoffs.	a (●), j (○)
6. Understanding of computer numerical control, how to write NC programs, and how to create NC programs with CAD/CAM software.	a (●), j (●) , k (●)
7. Ability to interpret engineering drawings.	a (●) , g(●), k (●)
8. Ability to look at products and determine how they were manufactured and why.	a (●) , e(●), i (●)

○ denotes moderate contribution to the outcome   ● denotes substantial contribution

An overview of the DFM course is illustrated in Figure 1. The course integrates the basic engineering fundamentals of the design process and manufacturing processes, including technical and economic tradeoffs, material selection and production practice. It strives to help students fully appreciate the interactions between product design and product manufacture.

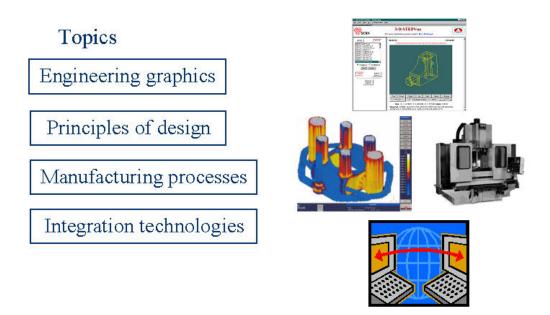[1] ABET 2005-2006 Criteria for Accrediting Engineering Programs

Figure 1. Overview of the Design for Manufacturing (DFM) course

IV. Course Content

The course uses a website that includes a week-by-week schedule that integrates design, manufacturing processes, engineering graphics, and computer-aided manufacturing topics[11]. A brief description of course content for each topic follows.

   Manufacturing Processes

The body of knowledge for manufacturing is immense, attested to by the number of pages in most manufacturing process textbooks, including the Kalpakjian textbook. The DFM course covers only the major manufacturing processes: material removal processes (milling, turning, and drilling), forming processes (forging, shearing, and bending), casting processes (sand and die), and assembly processes (discrete fasteners, fusion welding, solid-state welding, brazing and soldering). Other process topics covered include plastics processing, composites, inspection techniques, rapid prototyping, and surface treatments.

To learn these topics, students are expected to read the textbook, attend lectures, do textbook problems, and review process videos. When possible, emphasis is given to engineering analyses that reinforce design and manufacturing relationships. For example, the equations for calculating cycle times and horsepower requirements teach students to appreciate how design features can change cycle times (and cost), and how design features affect equipment selection. Tool selection is also explored and its effect on cycle time, tool life, and cost. Within sheet metal processes, bend allowance equations are taught so that students see how the raw material shape can be different from expected based upon the process and the material being used.

Engineering Graphics

Many faculty can remember taking a full year of engineering graphics when they were in college. We are now trying to fit this knowledge into less than half the semester-long course. Of course, CAD has replaced most mechanical drawing once taught (and sometimes, still are) in engineering graphics. Much discussion on what should and should not be included still occurs, and Dr. Jerz has presented his perspective in two papers at previous ASEE conferences[12,13]. It is believed that students should still have some sketching, drawing creation, and drawing interpretation education.

As a minimum, the following engineering graphics topics are included: orthographic and isometric views, working drawings, dimensioning, surface finish and machining symbols, inclined and rotational surfaces, isometric drawing, chamfers, repeated features, sheet metal developments, primary views, and auxiliary views.

Students must do almost weekly assignments on these topics. The assignments are modeled from the Jensen book on interpreting engineering drawings[14]. Some assignments include sketching and some include drawing interpretation.

Computer-Aided Manufacturing (CAD/CAM/CNC)

Pro/E is taught using the Toogood and Zecher book[9]. Eight of the book's ten exercises are assigned. Students learn to model prismatic and rotational parts, swept and blend features, and to create assemblies and drawings. The CAD exercises sometimes reinforce engineering graphics topics and vice versa. Figure 2 is an example of one student's part created in Pro/E.

Figure 2. Student's Pro/E Part

CAM is taught by introducing students first to the basics of NC programming. Students learn to write NC code manually that will produce a part that they machine on the Techno milling machine, during one lab session. Later in the course, they learn how to create NC code using the NC/POST module of Pro/Engineer® Complete Machining. The first semester that this course was taught, Mastercam® was used for machining. However, since the University owned only

three copies of Mastercam®, getting 50-60 students through this lab became a barrier. Our site license for Pro/E makes using Pro/Engineer® Complete Machining a more practical solution for the students because it is accessible on every computer on the College's network.

The students complete thirteen labs. CAD, CAM, and NC/CNC instruction is provided during "lab times," which are conducted during an extra hour (4th hour) each week. Three TA's help students complete the lab assignments.

Additional Topics

Manufacturing cost and product design tradeoffs are explored with a variety of simple product configuration assignments, and with some costing tools and techniques that Dr. Jerz developed for his PhD[15]. An assignment where students attempt to calculate the cost of chocolate-chip cookies illustrates some important lessons in determining product cost. This assignment emphasizes material cost, equipment utilization, and time considerations. Figure 3 shows an example of the cost analysis results in Excel (both input data and graph.)
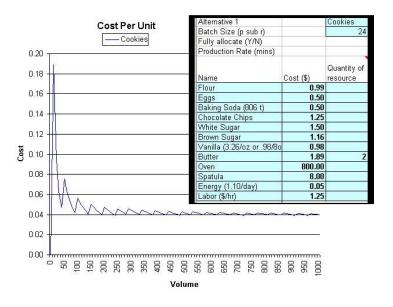

Figure 3. Cost Analysis Model

Several assignments relate to inspection technologies and techniques. A laboratory exercise challenges students to learn to use and read a micrometer and digital calipers.

A similar approach is used to teach rapid prototyping (RP) technologies. Students have readings and assignments, but they also have a lab where they design a part in Pro/E, create an STL file, and transfer the file to a computer in the College's Engineering Design and Prototype Center, which runs an RP machine. This is great technology for students to learn about, but the lab is not particularly challenging because creating an STL file from Pro/E takes about 10 seconds and little mental effort.

Integrated Design Project

An "Integrated Design Project" was added to the fall 2004 offering of the course because it was believed that students needed to see a closer integration of the many topics that are covered. The students work on this project throughout the semester. The students are challenged to apply their creativity and knowledge to a product design and manufacturing scenario. The student teams, comprising three or four students, are created to give them experience working with others. The students had to create their own vise design based on a product specification and an example picture of the vise. They had to document their design within a final report. Students were expected to brainstorm ideas, create sketches, create CAD models, create working drawings, and create some prototype parts. In addition, students had to tour a manufacturing company and write about their tours in one section of the reports.

The report was formatted according to an established engineering report standard. A report template for Microsoft Word was provided to the students. Teams that wanted to present their results could do so at the end of the semester for extra credit. Nearly all teams presented their projects. Figure 4 shows an example of one team's final vise design.
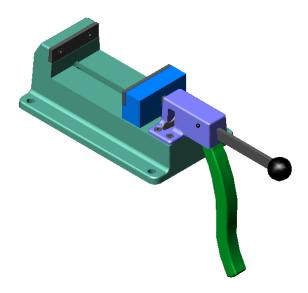

Figure 4. Example of Vise Design

V. Course Delivery Methodology

The DFM course is taught each semester in one section (limited to 60 students). ME students are encouraged to register for the spring semester, and IE students for the fall. However, so far, both sections have had both ME and IE students in them. Three, quarter-time teaching assistants support the instruction. The classroom provides complete audiovisual and computer technologies. A computer laboratory with 32 HP workstations is used for the Pro/E instruction. The machining laboratory has two Techno CNC machine tools: a 3-axis milling machine and a 2-axis lathe. A rapid prototyping machine is also available in the College's Design and Prototype Center.

Students are taught in either the classroom or one of the laboratories. Students are expected to attend class, turn in assigned homework and attend scheduled laboratory sessions for the supplemental instruction.

A course website was created to make instructional materials easily available to students. Students are expected to enter their textbook problem answers through WebCT as well as some engineering graphics drawing interpretation assignments.

Two "on-line" weeks were developed that allow students to complete readings and assignments at their own pace. The instructor does not hold a formal class during these weeks. Lecture videos were developed to support the on-line topics. The students can also use the common meeting time during these weeks to meet with their team members and work on the integrated design project. The TA's are still available during lab times.

A spreadsheet is used to record students' grades on homework assignments, lab exercises, exams, attendance, and the integrated design project. The instructor and the TA's edit the spreadsheet after grading assignments. Since there are more than 50 graded components for this course, progress reports are provided to students throughout the semester. One interesting note about the grading of the integrated design project is that all students provide grades for their teammates' contributions to the project.

VI. Results and Discussion

A course such as this one usually takes several semesters before it comes together well, and we are continuing to make minor adjustments in preparation for the spring 2005 semester. To date, approximately 110 students have taken the course. It is a challenge to fit all desired materials into this single course; class time is at a premium. The web-based course management system mentioned earlier, WebCT, provides the capability to give quizzes outside of class times. Three exams are administered during class times. In two of the exams, students perform a Pro/E design task, which is observed by the TA's. This approach helped us better assess how well the students have learned the CAD work. Doing this in the first exam gives students the motivation they need to learn Pro/E.

Student evaluation results are mixed. Some students think that the course is too hard and some think it is too easy. After the experience gained through the first offering and considering some "too easy" comments, a few more labs and the integrated design project were added.

The team-based design project was an experiment. The assignment was open-ended, which some students did not enjoy; these students seem to prefer a more structured project assignment. Some students are also uncomfortable making in-class presentations, and chose not to participate in this extra credit exercise. Nevertheless, the students wrote excellent project reports. Many teams came up with very creative designs. Some students had obviously mastered Pro/E.

Our limited tooling for the lathe and milling machine clearly taught students that often, creative and complex designs could not be manufactured! This was a major goal for the course – to help engineering students appreciate the need for close interaction between design and manufacturing

engineers. The rapid prototyping lab also illustrated a great technology for quickly producing design models.

The course is not without its problems. One of the biggest challenges is finding a book(s) that covers most of the topics and is affordable. We use about a third of the Kalpakjian book. Students selling it at the end of the semester can recover some of its expense. The Pro/E book is well done and matches our version of Pro/E, but it does contain some errors. The learning curve for Pro/E continues to be steeper than desired. The Pro/E software documentation is substandard, and many other Pro/E users have verified this.

Getting good teaching assistants is also a challenge. A good TA must be familiar with Pro/E, with manufacturing processes and with the operation of the CNC machines. Most of the TA's have been energetic and very helpful, and their student evaluations have confirmed this. The current version of the course comprises 34 homework assignments, thirteen labs, three exams, and a final project report. The TA's are actively involved with the students throughout the semester.

VII.   Future Direction

Fitting more information into the same amount of time continues to be a challenge. In the future, we plan to use even more instructional videos delivered through the website. This might be a good way to increase student exposure to more manufacturing processes. We believe that if we make some instructional material available to the students at their convenience, we can provide more learning material. We have found that creating the multimedia material takes time. Increasing the number of product-costing exercises could help students learn more about the significance of cost in the design process.

We plan to continue the integrated design project, but feel the need to set well defined milestones. It appeared that some teams did not spend enough time planning their projects. We also will probably vary the product that they can design or redesign.

A well-designed textbook for this course is still needed. It may be necessary to either author one or find a publisher that has the right components in several books and can create a custom book for us.

The learning curve for Pro/E and its inadequate CAM documentation are the most significant problems for this course. We will continue to look at other CAD products and especially other CAM products that might work better. Pro/E is a very capable integrated product and is used by many larger companies in our region, but a different CAM product might better support CAD/CAM education. We have found that many companies do not use Pro/E for CAM. The use of Catia® is being explored, and Dr. Jerz is using SolidWorks® and Surfcam® at St. Ambrose University. The CAD/CAM software market is continuously changing with new products becoming available each year.

A College-wide virtual manufacturing laboratory is being developed in our Active Learning Facility (ALF). Having virtual manufacturing software available may someday offer a more effective learning environment for students. The Delmia® CAD/CAM software suite will be

used to teach the complete product life cycle engineering basics to the DFM students in the future. The software will supplement instruction in product design, process selection and planning, human factors/ergonomics, robotics and production scheduling. Exploration into other support software, such as DFMA from Boothroyd Dewhurst[16], should be undertaken. Additional laboratory equipment also is planned to expand student learning of various manufacturing technologies, including quality control, automation and process control.

Concerning engineering graphics, we see a need to somehow add geometric dimensioning and tolerancing (GD&T) instruction. Since GD&T is a method of defining parts based on how they function, we believe there is an opportunity to link GD&T instruction with product design concepts and design intent. How and when to introduce GD&T have not been determined.

VIII.   Conclusion

The DFM course has been highly successful in meeting the educational goals of the MIE Department. Students enter the class with little or no experience with integrated manufacturing, and leave with considerable exposure not only to Pro/ENGINEER® but also to the principles of parametric design, computer numerical control, manufacturing processes, and engineering graphics, all within the context of an integrated design, development, and manufacturing environment. Students gain "hands-on" experience with what "design for manufacturing" really means.

Bibliographic Information

1. Massachusetts Institute of Technology, "Design for Manufacturing,"
    http://www-me.mit.edu/CourseListings/CourseListings.htm#Manufacturing.
2. University of Pittsburgh, "Design or Manufacturing,"
    http://www.engr.pitt.edu/mechanical/undergrad/courses/me1038.html.
3. Penn State, "Production Design," http://www.cede.psu.edu/StudentGuide/IET215.htm.
4. Stanford University, "Management of New Product Development,"
    http://www.stanford.edu/dept/registrar/bulletin/bulletin00-01/pdf/ManagSciEng.pdf
5. The University of Texas, "Industrial Design for Production,"
    http://www.me.utexas.edu/student/courses/me365l.shtml.
6. The University of Michigan, "Design for Manufacturing,"
    http://www.engin.umd.umich.edu/IMSE/courses/ABET/486.html.
7. The Society of Manufacturing Engineers, MEP, http://www.sme.org.
8. Manufacturing Engineering and Technology, S. Kalpakjian and S.R. Schmid, 4th Edition, Prentice Hall, Upper Saddle River, NJ, Copyright 2001. ISBN 0-201-36131-0.
9. Pro/Engineer Wildfire2.0 Tutorial, Roger Toogood and Jack Zecher, SDC Publications, 2004.
    ISBN 1-58503-186-0.
10. ABET Accreditation Evaluation 2005-2006 Criteria, http://www.abet.org/images/Criteria/E001%2005-06%20EAC%20Criteria%2011-17-04.pdf.
11. The University of Iowa, "Design for Manufacturing," http://www.engineering.uiowa.edu/~mie032/index.htm.
12. Jerz, R., "How CAD Forces Changes to Engineering Graphics Education," ASEE Annual Conference, Albuquerque, New Mexico, June 2001, http:// web.sau.edu/JerzRichardJ/Professional/Professional.htm.
13. Jerz, R., "Redesigning Engineering Graphics to Include CAD and Sketching Exercises," ASEE Annual Conference Proceedings, Montreal, Canada, June 2002.
14. Interpreting Engineering Drawings, 6th Ed., Cecil H. Jensen, Delmar Thompson Learning, United States, 2002, ISBN 0-7668-2897-2.
15. Jerz, R., "A Resource Consumption Model (RCM) for Process Design," Ph.D. Dissertation, The University of Iowa, Iowa City, Iowa, 1997.

16. Boothroyd Dewhurst, Inc., Design for Manufacturing and Assembly (DFMA), http://www.dfma.com/.//www.dfma.com/.

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