

Design and Manufacturing Education through Re-engineering Products*

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Integrated design and manufacturing using rapid prototyping, polymer processing, casting, and automated inspection can revolutionize product design and manufacturing, particularly of labor-intensive and costly low-volume, high-end parts. To infuse manufacturing industries with new practices, engineering education in these areas should target laboratory experiences that stretch the student's imagination regarding how such processes can be used. This paper describes design and manufacturing laboratories based on product re-engineering that form the core of a studio-based computer-aided design and manufacturing course. Outcomes of classroom use of these laboratories are summarized. The course integrates design, engineering analysis, and manufacturing, provides hands-on experience with molding and CNC manufacturing processes, incorporates rapid prototyping within the design process, and provides experience with state-of-the-art metrology.

INTRODUCTION

THE DESIGN AND manufacturing laboratories described in this paper have been developed for an upper-level computer-aided design and manufacturing (CAD/CAM) course at Dartmouth College. Students that populate the course range from Bachelor of Engineering (B.E.) students (fifth year) to Master of Engineering Management and M.Sc. degree candidates from traditional mechanical engineering programs, both in the US and from German and Swedish exchange programs. Dartmouth's sole undergraduate engineering degree is in engineering science, thus, unlike a traditional mechanical or manufacturing engineering core curriculum, students do not take sequenced courses in engineering drawing, design, product design, and manufacturing leading up to a culminating CAD/CAM course. Instead, the CAD/CAM course is a one-quarter (ten-week) elective that follows strength of materials and machine design. Course preparation normally includes three-dimensional solid modeling, design drawing preparation, manufacturing using traditional machine tools, and design and analysis of machine components, including static and fatigue failure and deflection, all of which are covered in a one-quarter machine design course. In addition, students understand and have experience with the design process through one or more prior courses, and some students have already completed a capstone design sequence taken prior to the CAD/CAM elective, albeit not as a prerequisite. The course is specifically structured with only the machine design prerequisite, such that qualified juniors or seniors can enroll as well.

The objectives of the CAD/CAM course are to:

- develop advanced three-dimensional modeling capabilities;
- enable students to understand and relate the product design cycle to product manufacturing through experiential learning;
- enable students to use design optimization methods effectively; and
- provide hands-on experience with a variety of manufacturing processes, including plastics processing, NC machining, rapid prototyping, and automated inspection.

To meet these objectives, a series of design and manufacturing studios have been developed that focus on re-engineering an existing product related to a pastime, sporting activity, consumer use, or other similar application. The product design focus provides avenues for design optimization, engineering analysis, and manufacturing of components that can then be retrofitted into an existing product and tested, all within a one-quarter course. This paper describes the CAD/CAM facilities, course structure, integrated CAD and CAM studios, and project assignments, and summarizes tangible outcomes and instructor observations of studio-based CAD/CAM learning experiences.

FACILITIES

The machine shop at the Thayer School of Engineering, Dartmouth College, is an instructional workshop and design center supporting student and faculty research, instruction, and project activities. The shop is divided into seven areas, of which four are heavily used in the CAD/CAM course. Four full-time technical instructors

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and one part-time professional design consultant staff the facility, together with a large corps of temporary and part-time student assistants.

The Design Center includes nine networked Dell Pentium 4 Workstations with Pro/Engineer design software, Pro/Mechanica, and Pro/Verify. FeatureCam is used to create manufacturing models from Pro/Engineer design models. A separate multifunctional classroom with 18 workstations accommodates CAD studios. The machine shop Design Center supplements these facilities by providing CAD resources in close proximity to manufacturing equipment.

The Polymer Processing Center includes a Formech 660 Thermo-Forming Machine with capacity of 26" square, up to 16" depth of draw; two Morgan Injection Molding Presses with a 4-ounce volume, 20-ton capacity; an MK Technology vacuum casting machine with mold area 450 mm × 470 mm × 400 mm; and three Stratasys rapid prototyping Fused Deposition Modeler (FDM[®]) rapid prototyping machine. The FDM process creates solid models directly from 3D CAD files using structural materials, such as polycarbonate and ABS, as well as wax. The three machines include a Stratasys 1600 with a build area of nine cubic inches, a Stratasys Titan with build area 14" × 16" × 16", and a Stratasys Prodigy Plus with build area 8" × 8" × 12". Each machine can produce prototypes in ABS. The Titan and 1600 also use polycarbonate, and the 1600 has the capability of producing a wax prototype. The vacuum casting machine allows production of parts in small quantities from silicone molds. It accommodates a rapid prototype or an existing part as a pattern to create a soft mold, which can then be used to create parts in a variety of thermoset urethane compounds.

Inspection/Quality Control equipment includes a Brown and Sharpe Model PFX 454 Direct Computer Control Coordinate Measuring Machine, 'Tutor For Windows' inspection software, 18" × 20" × 16" work piece capacity, as well as a complete set of micrometers for up to 12" and an 81-piece set gage block inspection set traceable to the National Bureau of Standards. Additional equipment for inspection includes a Capture Graphics Inside (CGI) Reverse Engineering Machine and SpeckCheck[®] Software. The reverse engineering process provides point cloud data by destroying a part.

The CNC Center includes a Bridgeport Series II Interact 4 Knee-Type CNC Milling Machine, with Heidenhein TNC 2500 Control and 4000 rpm maximum spindle speed; a Bridgeport/Romi Centur 35 E CNC lathe, Fanuc 0-TC Control; and a Haas VMC Super Mini Mill high-speed machining center, with a 15000 rpm maximum spindle speed.

In addition to CNC and polymer processing equipment, the machine shop maintains a host of traditional machine and hand tools, including vertical milling machines, manual engine lathes,

pedestal drills, bandsaws, cut-off saws, buffing/polishing, grinding and glass-bead blasting. Welding and fabrication facilities for MIG and TIG welding are also available.

DESCRIPTION OF CAD/CAM LABORATORIES

The CAD/CAM course is conducted in a studio format, with the class divided into two groups that rotate between CAD and CAM studios, spending one two-hour period in each studio during a week. During CAD studios, students work through tutorials prepared by the instructors on topics ranging from advanced solid modeling to structural and thermal analysis. CAM studio time is used to work on assigned manufacturing projects. CAD and CAM studios are tightly integrated, such that CAD studio curricula and follow-up assignments play directly into the design of products and/or tooling to be manufactured by students during CAM studios. Students work on projects in teams of two or three. Each team has a three-hour lab period outside of regular class hours for manufacturing work, and an open CAD classroom is maintained for design work performed outside of studio time. It is expected that students spend a 12–15 hours per week on coursework, including in-class studio and laboratory time.

The rotation schedule and material preparation, though labor-intensive for instructors, maximizes use of resources, as the entire class cannot fit into either the CAD or CAM facilities at once without sharing computers or manufacturing resources. Moreover, technical machine shop staff play a major role in instruction and evaluation of student work, effectively quadrupling the teaching staff for the course. Within the CAM studio, students rotate through a series of five to six in-depth manufacturing exercises aimed at completing their project assignments. The rotation is sequenced such that, during CAM studios, groups work with different equipment. For example, one group may be involved in mold-making using CNC equipment, while a second is using the vacuum casting machine or preparing a manufacturing model in the design lab. As in an industry manufacturing environment, students may submit jobs involving long build times to a queue, and, once set up, the jobs run unattended overnight.

CAD studios cover advanced solid modeling and progress to engineering analysis (thermal and structural) using Pro/Mechanica. After each studio, students are given a CAD and CAM assignment related to the studio material. For example, the first studio covers advanced feature creation, such as sweeps, blends, copying, and creation of features from splined point data. The CAD assignment following this studio involves design of a product that must incorporate such features and that will be manufactured by injection molding or vacuum casting. Table 1 provides

Table 1. Sample descriptions of CAD and CAM studios and prerequisite material

Studio	Content	Prerequisites
CAD 1	Advanced CAD part design. Blends, patterns, copying, dimension relations. Creating geometry from point data (splined curves).	Familiarity with CAD to the level of a typical first-year course in AutoCAD, Pro/ENGINEER or other such packages
<i>CAM 1</i>	<i>Rapid prototyping I</i>	<i>None</i>
CAD 2	Advanced CAD design (cntd). Draft, rounds and their functions. Mold design. Parting line selection. Male vs. female molds.	CAD 1
<i>CAM 2</i>	<i>Vacuum casting</i>	<i>None</i>
CAD 3	Open studio to support design/modeling questions	CAD 1 and 2
<i>CAM 3</i>	<i>CNC milling; automated NC code generation</i>	<i>CAM 1</i>
CAD 4	FEM for structural analysis. Loads and constraints. 2D vs. 3D approximations. Stress concentrations. Advantages and limits of FEM.	Machine design, strength of materials
<i>CAM 4</i>	<i>Injection molding or thermoforming</i>	<i>CAD 1 and 2</i> <i>Plastics manufacturer field trip</i>
CAD 5	Design optimization. Identifying design parameters and optimizing a goal subject to structural constraints. Gradient-based optimization.	CAD 4, Calculus
<i>CAM 5</i>	<i>Advanced topics: composites, investment casting</i>	<i>CAM 4</i> <i>Foundry field trip</i>
CAD 6	Finite-element modeling (FEM) for modal and thermal analysis.	Introductory thermodynamics or fluid mechanics
<i>CAM 6</i>	<i>Coordinate Measuring Machine lab</i>	<i>CAD 1</i>
CAD 7-8	Finite-element analysis of assemblies. Mesh generation and modeling of contacts.	CAD 1-6
<i>CAM 7-8</i>	<i>Open studio for project manufacturing</i>	<i>CAM 1-6</i>

sample descriptions of CAD and CAM studio content and prerequisite material.

In addition to CAD and CAM studios, homework assignments are given to reinforce CAD material, particularly that related to structural analysis. In homework exercises, students must relate analysis methods learned in a traditional machine design course to similar analyses performed with finite-element software. For example, students must infer stress concentration factors and determine static and fatigue safety factors using both hand calculations and stress analysis performed using software. Homework assignments apply such concepts to relatively simple parts (e.g. plates with holes in axial tension or bending, and round bars with fillets under torsion and bending). CAD assignments subsequent to homework exercises involve analysis and optimization in which students must extend these concepts to complex parts.

CAD and CAM assignments that follow studio exercises provide a central theme around which all individual projects for the term are based. Sample themes used since the inception of the studio model include re-engineering of a popular scooter (spring 2001), a model airplane design (spring 2002), a plastic tricycle (spring 2003), or a radio-controlled sailboat (spring 2004). Each project begins by building on basic and advanced CAD instruction provided in CAD studio one, while providing a design with which to begin CAM activities during the first week of the course. The first CAD assignment for the scooter theme is to design a handlebar 'clip' with increased functionality over the existing clip. The redesigned clip must hold a light, basket, or water bottle. The clip is rapid prototyped in ABS in an early CAM assignment, assessed for functionality, and modified as necessary. In the

following CAD assignment, a mold is designed from the part model, and parting lines are selected. In the next CAM assignment, NC code is generated, and the mold is manufactured using a CNC mill. Finally, the part is manufactured by injection molding and evaluated for functionality and quality.

A second series of assignments targets redesign of the scooter base and folding mechanism to support required loads, while reducing mass and complexity. The design process involves determining structural loads, modeling load transfer to and appropriate constraints on parts to be designed, structural analysis and evaluation of static and fatigue safety factors, and optimization. These parts are manufactured using a variety of processes, from CNC machining to composite lay-ups. The parts are then interfaced with existing parts of a scooter (handlebars, upright, and fork), resulting in a working scooter.

The second thematic project is the design of a thermoformed model airplane and its two-stroke glow plug engine. The model airplane, with its aerodynamic geometry, need for simplicity in assembly, and need for low mass represents an excellent opportunity for students working in different groups to collaborate in the design process. To this end, each team is assigned a 'part' of the airplane: the wing, fuselage or tail section. Specifications require final parts to be assembled, thus designs are shared in common space on a networked hard drive, such that final assemblies can be evaluated. Aerodynamic sections are required for wings, providing an avenue for developing splined curves from aerodynamic analysis that provides point data for a wing section. The manufacturing processes require selection of male vs. female molds, mold-making

by CNC machining, and thermoforming multiple parts.

A second series of studios focuses on analysis of the static and dynamic loads on a two-stroke, glow plug engine, and redesign of the engine to minimize mass, while retaining adequate safety factors. The engineering design process for the engine integrates basic concepts in thermodynamics, heat transfer, and structural analysis. As with the scooter project, the design process involves determination and modeling of structural loads and constraints, structural analysis and evaluation of static and fatigue safety factors, and optimization. Thus, for crankcase analysis, students begin with a thermodynamic cycle to determine cyclic pressure loads on the cylinder and bearing loads on the crankshaft case. They then model these loads, along with appropriate constraints, and evaluate stress in the engine material. Based on results, they estimate static and fatigue safety factors. In a subsequent assignment, students choose a few critical parameters and optimize these to minimize mass, subject to a required safety factor. The resulting designs are prototyped in wax or ABS, to be investment cast. For FEM, students must identify and suppress features that they anticipate will cause fictitious stress concentrations, and symmetry of the engine is used to enforce FEM practices that simplify computation.

The third thematic project involved re-engineering a tricycle. Early projects include the design of an ergonomic handlebar grip, which is rapid prototyped and vacuum cast in early CAM studios, and the design of a wheel hubcap, which is injection molded over through a series of CAM studios and associated CAD assignments. As with

the airplane theme, each team is assigned one of three sub-assemblies to design the remainder of the tricycle: the fork and handlebar, the frame and seat, or the wheel and pedal/crank assembly. Each sub-assembly requires structural design and optimization, as well as consideration of ergonomics. Manufacturing facilities for constructing the prototype tricycles include the CNC equipment and the Stratasys fused deposition rapid prototyping equipment.

Individual development projects tailored more narrowly to a specific manufacturing process have also been evaluated, rather than projects related to a central theme. This style allows us to revisit and refine some of the more successful aspects of thematic projects. As an example, one team evaluated the ability of vacuum casting and reverse engineering to develop methods for metrology of worn knee implants. A key specification of the metrology process is that measures of wear must be made without destruction of the original part, as the worn part is required for further research. Thus, the metrology process involves making a copy of the implant using vacuum casting, reverse-engineering the copy to obtain point cloud data, and making measurements on the point cloud data to characterize wear. The engine redesign project has also been assigned as a non-thematic project, in which students resize an existing 1.0 h.p. engine for a lower power rating. This project provides several design paths, from maintaining the original bore size and stroke while reducing internal pressure, to modifying bore size and stroke and using higher pressures. During and subsequent to the project, students are encouraged to share and debate their design approaches with

Table 2. Sample descriptions of CAD and CAM assignments following studio instruction

Studio	Scooter assignment	Model airplane and engine	Tricycle assignment
CAD 1	Handlebar clip with added functionality	Model airplane component design (for thermoforming)	Handlebar grip design
CAM 1	Handlebar grip design	Engine cylinder head design	Initial design concept for an injection molded hubcap
CAD 2	Create a scooter or airplane name tag by CNC engraving using 1) hand coding and 2) automated code generation	Design a thermoform mold to manufacture a model airplane part	Rapid prototype grip and use it to vacuum cast the grip
CAM 2	Design an injection mold to manufacture the clip	Design a thermoform mold to manufacture a model airplane part	Hubcap design revision for injection molding constraints
CAM 2	Rapid prototype clip, grip, cylinder head, or other part from CAD1; test for functionality and revise part/mold design accordingly		NC code for complex parts; importing geometry, tool path definition, complex surfacing
CAD 3	No new assignment; catch up	No new assignment; catch up	Create a two-part mold design with a multi-level parting line
CAM 3	Create a manufacturing model for the clip, airplane part, or other part from CAD1; automatically generate NC code; make the mold using an NC mill		Create a manufacturing model for the hubcap; manufacture using CNC mill
CAD 4	Structural analysis of two critical scooter parts	Structural analysis of two critical engine parts, one being the crankcase	Design tricycle sub-assembly
CAM 4	Injection mold, thermoform, or vacuum cast parts from previous CAD assignments		
CAD 5	Optimize scooter parts to minimize mass subject to structural specifications	Optimize engine parts to minimize mass subject to structural and thermal specifications	Finalize tricycle design, manufacturing process, and assembly methods
CAM 5	Introduce other manufacturing process, such as manufacturing composite lay-ups or investment casting; through this studio, students decide whether such a process is appropriate for a project part		Tricycle manufacturing

each other and to compare results, thus aiding the learning process. One interesting aspect of this project is that 15 distinct design approaches were taken in a class of 22 students, and all the design approaches were valid and defensible.

In all projects, students play a direct role in all manufacturing tasks. While machine shop instructors are always available to assist, students generally become proficient at using NC code generation software, setting up parts and tooling for NC machining, and using plastics processing and molding equipment independently. Table 2 summarizes CAD and CAM assignments given to students at the end of each CAD studio for thematic projects.

RESULTS

Scooter redesign theme

Figure 1 shows one mold, and several final clips for the scooter redesign project, along with a redesigned steering/folding assembly and scooter base. The clip design, though appearing to be simple on the surface, brings out significant issues associated with assessing functionality, tooling for injection molding, and the injection molding process. The clip underwent additional redesign steps after initial three-dimensional solid models were created. Functionality was tested using a rapid prototype of the initial clip design, and the first design iteration corrected any defects in functionality. Next, as students were limited to a 4-ounce shot capacity and a three-axis mill for mold manufacturing, a second modification of their designs was sometimes required in order to accommodate manufacturing constraints and tooling. Though symmetric clip designs were the norm, several groups designed clever asymmetric clips that required only a two-piece mold and a single level parting line. Although students were not capable of anticipating all effects of the



Fig. 1. Sample results of scooter project: clip mold, sample clips, re-engineered steering and hinge assembly, and composite scooter base.

manufacturing process on their design (which was not expected), they quickly learned the value of concurrent design and manufacturing, and experience-based learning proved to be a valuable method to instill these concepts.

Scooter folding and steering mechanisms were redesigned and evaluated using Pro/Mechanica and were manufactured using CNC milling. An interesting aspect of this project was that no two groups arrived at even remotely similar designs or design approaches, all mechanisms worked the first time, and optimization results were substantial, with mass reductions of more than 50% of the initial mass. Scooter base designs also varied substantially, and several groups opted for a composite design, which involved manufacturing a mold using the CNC mill from which a hand carbon-fiber composite lay-up was made. The design and structural analysis of the composite base was performed using Pro/Mechanica with mixed success, as the hand lay-up process is difficult to model. In essence, the analysis provided students with the number of layers necessary to meet structural requirements, as well as an estimate of the mass of the final product, but could not capture the effects of inconsistencies in the manual lay-up process. Nevertheless, these projects provided nice examples of how manufacturing methods and materials for the prototype played into choosing optimization parameters.

Model airplane theme

Figure 2 provides a snapshot of project outcomes within the model airplane theme. As with the scooter project, the course began with a CAD assignment related to design, in this case of a wing, tail, or fuselage section of the airplane. The class was divided into six teams of three students, with two teams assigned each part. Thus two different airplanes were constructed by the class: a high mount wing airplane, and a second, low-mounted wing with double dihedral. The airplane parts provide excellent venues for introducing advanced features, such as sweeps, blends, and features from splined curves. A wing section design website from NASA provided point data from which to design the wing section in order to produce sufficient lift (<http://www.grc.nasa.gov/WWW/K-12/airplane/foil2.html>). Once designs



Fig. 2. Sample results of model airplane project: thermoform molds, thermoformed parts, aircraft assemblies, engine crankcase wax prototype, and cylinder head prototypes.

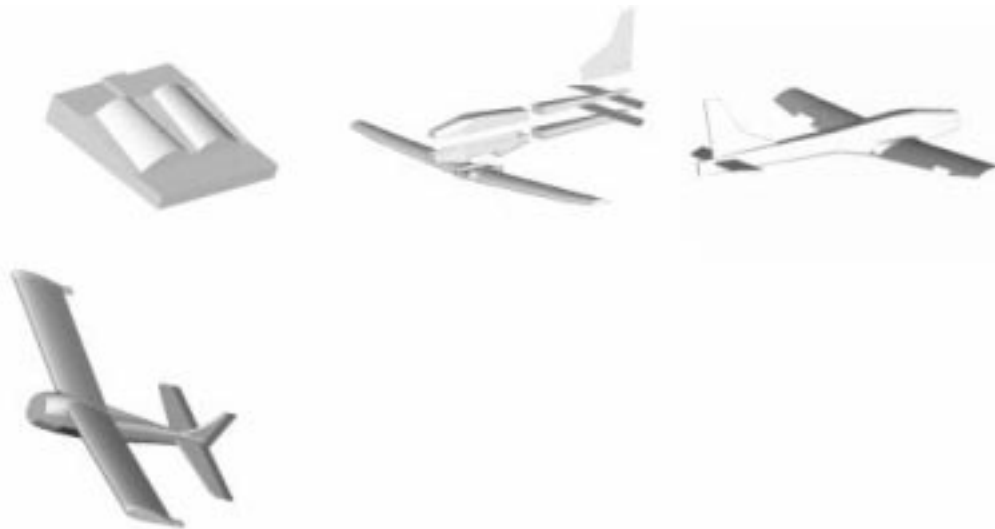


Fig. 3. Thermoformed airplane models, sample mold model for wingtip, assemblies of two model airplanes designed by student teams.

were finalized, they were assembled electronically with those from other groups, and molds for thermoforming airplane parts were designed. Figure 3 shows sample solid models. The process of making and finishing molds took several weeks, and substantial iteration of thermoforming and finishing was often required to obtain a good part, but, in the end, every team was successful in part manufacturing.

Concurrent with manufacturing efforts, students were learning material for structural analysis and design optimization in CAD studios, and were applying this material to analysis of thermal response of a model airplane cylinder head and structural response of the crankcase. The outcome of this component of the course was a redesigned engine crankcase and cylinder head, which reduced overall mass and/or improved heat transfer without changing the mass. Students determined structural and heat loads on their engine components based on the engine power rating and thermodynamic analysis, applied the loads to the part, and optimized critical dimensions to meet static and fatigue safety factor or thermal specifications. Figures 4 and 5 show sample outcomes of this process. The engine crankcase was then prototyped in wax for investment casting. The course concluded with informal presentations by student

teams, whereby they related their design process and experiences with manufacturing processes.

Tricycle theme

Having successfully completed two thematic projects, the third studio-based course offering sought to increase design sophistication within CAD and CAM assignments. The tricycle hubcap project took the molding process to a new level in allowing for a design that incorporated sophisticated sweeps and blends, as well as a multilevel parting line. This assignment was conducted over several weeks. Subsequent to the first CAD studio, in which students learned or reviewed sweeps, blends, and patterns, students were asked to develop a hubcap design using such features, while anticipating that the manufacturing method would be injection molding. Over the course of additional design iterations, students evaluated their designs for potential parting lines, anticipated features that would be most difficult to CNC machine, eliminated sharp corners, evaluated the ability to manufacture the mold using existing tooling, selected potential injection locations, and evaluated moldability using Pro/PlasticsAdvisor.

An example design is shown in Fig. 6. Using Pro/PlasticsAdvisor, the group found that the thick ribs contributed to low quality and potential

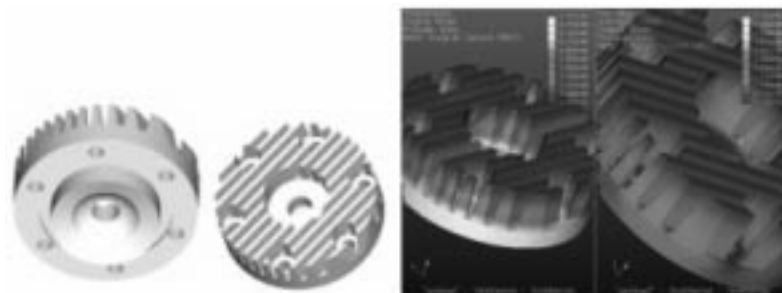


Fig. 4. Sample cylinder head model and thermal analysis.

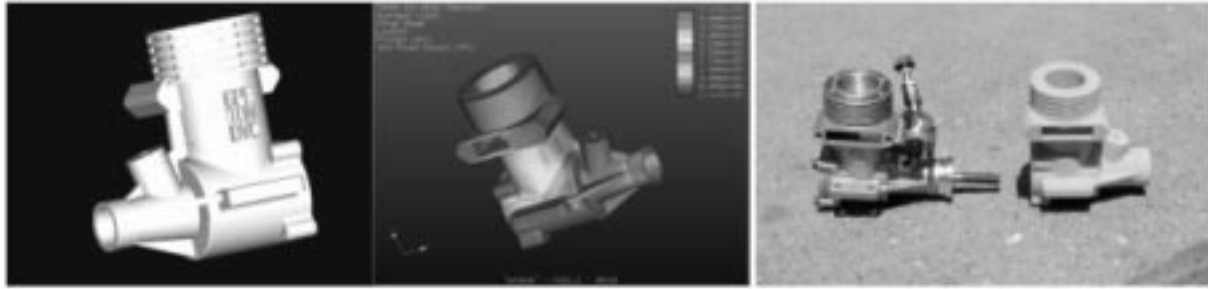


Fig. 5. Sample optimized engine model, engine analysis, original engine crankcase, and wax prototype of optimized design.

for sink, and thus they modified their design accordingly prior to manufacturing. Once each group had finalized their mold design, they generated NC code. During NC code generation, several groups again simplified some aspect of their design, as they realized that existing tooling would not provide the required features. The outcomes of this project were excellent. Figure 7 shows three molds, varying in degree of difficulty and part quality from average (left) to excellent (right). The middle mold is the design shown in Fig. 6. The design to the far right is one where the team performed well in anticipating requirements for the molding process early within the design stage, resulting in few design iterations.

Example outcomes of the tricycle design project are shown in Figs 8–10. Figure 8, which shows one

of three tricycles at both the initial design and final product stages, is nearly completely comprised of parts rapid prototyped in polycarbonate, providing a functional prototype. Although, once set up for rapid prototyping, the manufacturing was 'hands-off', students had to think carefully about how to design for and package their part within the rapid prototyper workspace in order to retain structural strength. For several groups, this required additional design modification, in order to fit the part so that material layers were deposited along appropriate directions, or to minimize build time. The initial design concept shown in Fig. 8 was revised to reduce build time by reducing material usage in the seat and backrest. Sample design analyses are shown in Fig. 9 for the fork assembly of this tricycle, for an impact loading

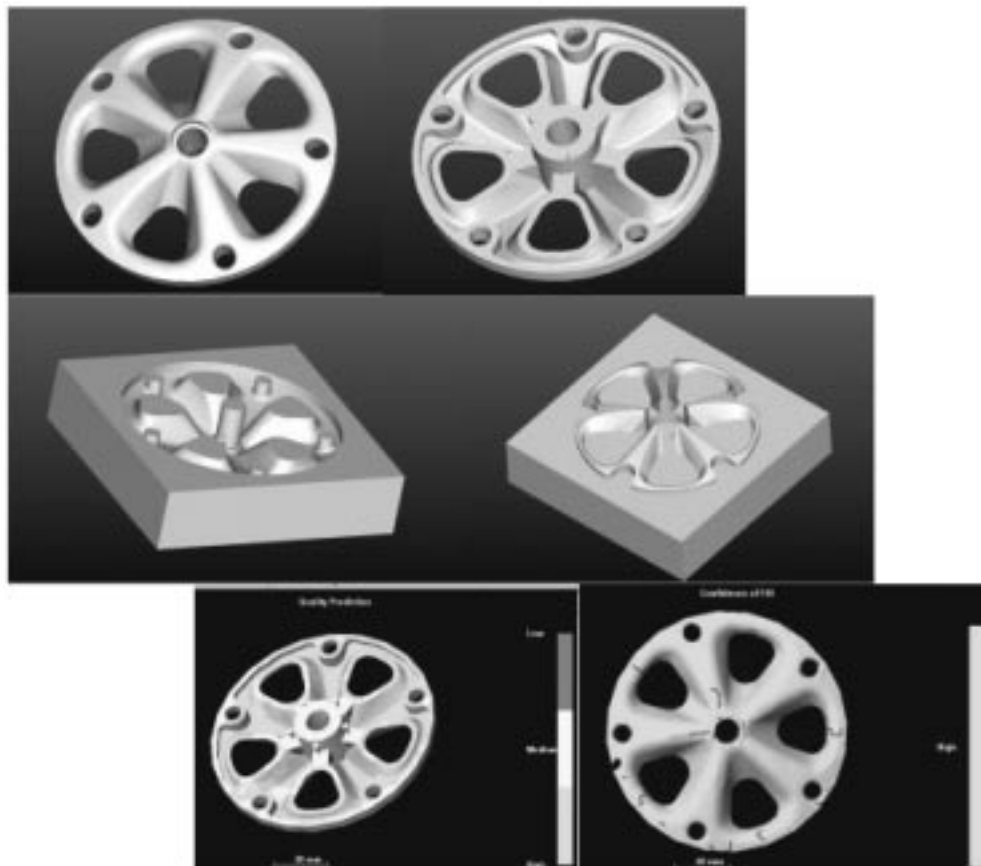


Fig. 6. Sample hubcap mold design process from top left to bottom right: part top and bottom, two mold halves, and sample analysis of mold quality and weld lines.

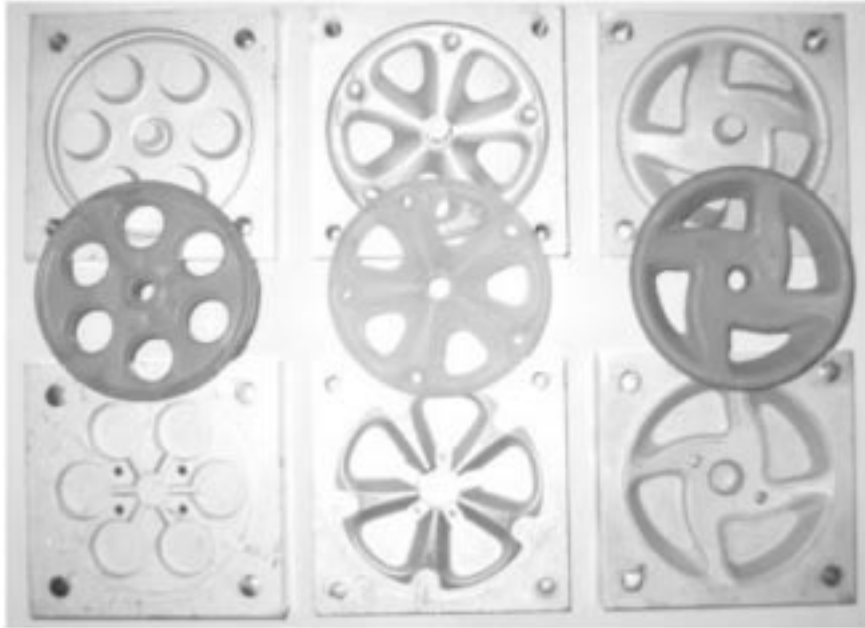


Fig. 7. Sample student-designed injection molded hubcaps and their molds.

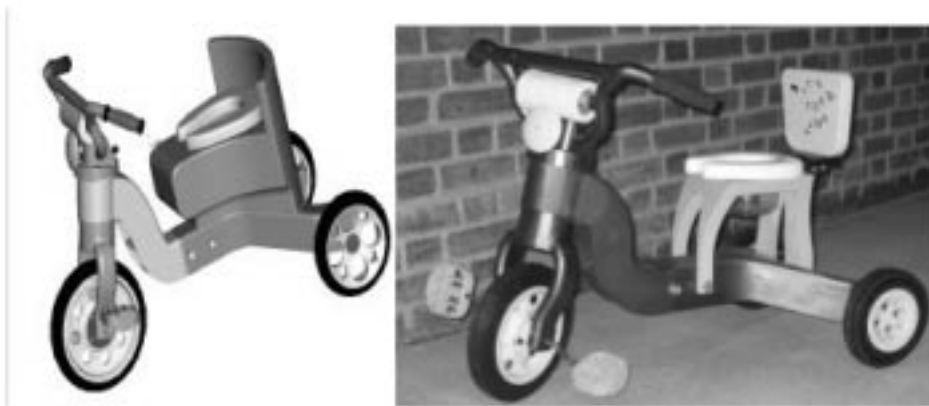


Fig. 8. Tricycle design concept (before revision) and final product.

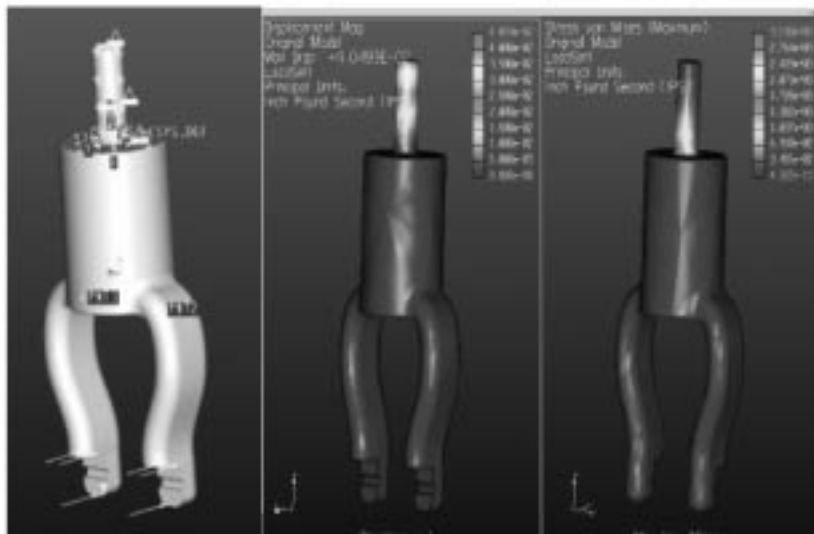


Fig. 9. Tricycle fork analysis for curb impact loading.



Fig. 10. Tricycle rim design for tubular tires and structural analysis results.

case of the tricycle hitting a curb. Several loading cases were considered, including the static loading, vertical impact loading, and horizontal impact loading, each with its own set of loads and constraints. Each team was required to translate loading conditions into appropriate forces and constraints on their part or sub-assembly, in order to provide safety factors. The wheel design proved to be an excellent project for dynamic loading analysis and fatigue safety factor computation, as well as a challenging design both in aesthetics and in mating with an existing tire. Figure 10 shows a wheel rim designed for a second tricycle, which accommodated tubular tires, along with sample structural analyses. The analysis involved translating loads transmitted through the hub and constraint provided by the road into appropriate FEM loads and constraints; simplifying the analysis using symmetry, and optimizing the spoke parameters in order to meet safety factor and deflection specifications, while minimizing mass. The manufacturing process used to machine the rim, which is made of acetal, included both NC turning and milling, and thus required substantial forethought in determining the manufacturing sequence.

OBSERVATIONS AND EXTENSIONS

The concept of re-engineering products for teaching CAD/CAM concepts as presented in

this paper targets students with a broad engineering science background who are in the last year of a bachelor's degree program or first year of a graduate program. However, it can be tailored to accommodate a broad range of student backgrounds. A key objective of Dartmouth's course is integrating finite-element engineering analysis in the design process, enabling students to assimilate material from a prior machine design course, while tackling more sophisticated design analyses than can be performed by hand calculations. To this end, projects are required to have a significant engineering analysis component. Other projects that fit the re-engineering theme include: hair dryers, leaf blowers, and vacuum cleaners, which can be designed to reduce noise and vibration and improve flow and efficiency; bicycle cranks, chainwheels, and suspension components, which can be designed to minimize mass while meeting structural requirements; or disc brakes for mountain bikes or vehicles, which incorporate both structural and heat transfer specifications. One can also envision an appropriate level of engineering analysis in products such as sprinklers, skateboards, and model sailboats. In traditional mechanical and manufacturing curricula, which include sequenced courses, it is possible to require courses to be taken concurrently, such that CAD/CAM courses build directly on content covered in a traditional 'companion' core course, such as strength of materials. Though this presents

more of a challenge in coordination, planning, and instruction, it is through such venues that curricular innovations are possible.

Prior to initiating the studio format, the CAD/CAM course was taught in a traditional lecture format using a textbook and covered material such as NC machine code generation, trajectory following, the geometry of modeling, and introductory finite-element analysis. Though suited for the 1980s and 1990s, even the most recent CAD/CAM texts now appear to be less relevant to responsibilities of those involved in product design and manufacturing. The studio course structure is well received by students and well suited to the future generation of engineers who will be charged with increasing efficiency and reducing cost in the complete design-manufacturing cycle, while producing competitive, high performance products. Instructional materials for such a course are largely unavailable through large textbook publishing companies, thus they must currently be developed and kept current by faculty and instructional staff members, as is done in Dartmouth's CAD/CAM course.

CONCLUSIONS

This paper summarizes the three-year evolution of design and manufacturing laboratories developed and tested in an upper-level CAD/CAM studio course for students in an engineering science program. The studio venue provides an experiential learning environment in which students are allowed to make mistakes, design iteration is expected, resources exist to support integrated design and manufacturing, and project assignments have relevance to traditional courses, such as strength of materials, machine design, and thermodynamics. This integrated approach to design and manufacturing education, though labor and material intensive, can be tailored to programs with more modest facilities and to students at different academic levels.

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Kevin Baron, Thayer School Instructor and Machine Shop Manager, received his ALB degree from Harvard University. Prior to joining Dartmouth College, Mr. Baron was Senior Manufacturing Engineer at the Webster Valve Division of Watts Regulator Corp, where he led the set-up reduction effort as part of that company's initiative to implement lean manufacturing strategies. Prior to that, Mr. Baron completed an eight-year term as Technical Instructor at MIT. In this capacity, Mr. Baron delivered the lab portion of MIT's 'Introduction to Manufacturing' course, in which he developed and executed exercises to introduce students to principles of CAD/CAM, CNC machining, CMM operation, and tool design. Twenty years of machine shop experience preceded Mr. Baron's arrival at MIT.