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A Systems Approach to Manufacturing as Implemented within a Mechanical Engineering Curriculum

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Recent innovations implemented towards the goal of improved manufacturing education within a small mechanical engineering department are described. The paper discusses evolution of curricular and facility improvements, the program objectives, the constraints bounding the developments, and the effects of completed modifications. Initial efforts targeted the need to incorporate hands-on laboratory experiences within the introductory manufacturing processes course. Subsequent activities have involved curricular adjustments focused on the integration of design and manufacture, and on the associated use of geometric dimensioning and tolerancing practices. Most recent improvements include the development of an elective course in computer aided manufacturing, the impact of an evolving manufacturing research program, and the value of a partnership with the local Small Business Development Center.

INTRODUCTION

WEAKNESS IN DESIGN and manufacturing capabilities in US companies is often cited as a crucial factor in the decline of the nation's global competitiveness. Several studies focused on this deficiency have concluded that the American manufacturing industry would benefit from a more integrated approach to product development, including a greater focus on the practice of concurrent engineering techniques [1]. In striving to improve the profitability of US products and the underlying design and manufacturing practices further, two key issues continue to warrant attention and improvement:

1. the traditional separation of the product design function from the related manufacturing tasks.
2. the lack of a true appreciation for the process of manufacturing as an integrated system [2].

Both industry and academia have responded to these needs with a nationwide effort to improve the way in which companies carry out the product realization process, including a systematic reform affecting the way in which universities teach these concepts within undergraduate curricula. In an effort to educate engineers that are capable of competing in the national and global marketplace, as well as continually adjusting to address the advances in associated materials, fabrication methods, and computer aided techniques, associated curricula must further focus on the integration of product development activities.

In the past decade, many universities have adjusted their manufacturing curricula to reintroduce hands-on fabrication experiences in conjunction with lecture materials on the theory and analysis of basic product development tasks. Previously viewed more as technical training in machine operation, computer aided advances of the 1980s and early 1990s emphasized the role of manufacturing in a complex product realization process [3]. Advances in flexible manufacturing, automated and robotic controls, material handling, and rapid prototyping, for instance, warranted major curricula adjustments. Schools benefiting from the presence of industrial and/or manufacturing departments were able to make substantial modifications and improvements through interdepartmental collaboration and organization. Similarly, universities with a large faculty base, benefited from the atmosphere associated with a strong, versatile manufacturing research program.

In contrast, the department of Mechanical Engineering (ME) at Bucknell University consists of only eight full-time faculty members, 130 undergraduate majors, and approximately eight graduate students. Without the benefit of an industrial engineering or manufacturing department, Bucknell's efforts towards improved integrated manufacturing education are uniquely constrained. This paper presents departmental accomplishments to date towards developing and implementing a program that supports a systems view of manufacturing and emphasizes the importance of integrating product development activities.

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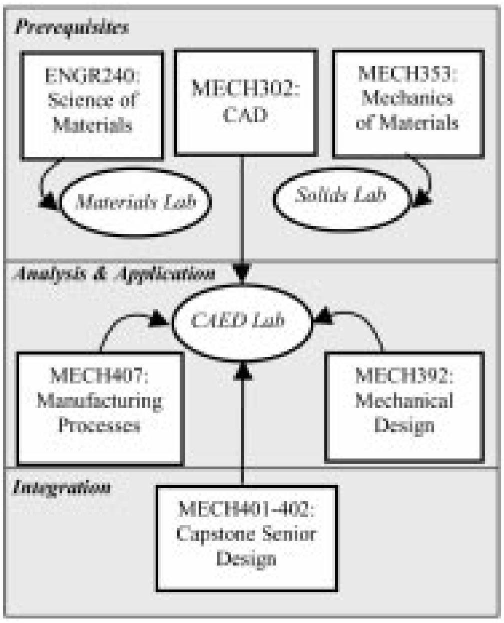

Fig. 1. ME Design/manufacturing curriculum in Fall 1996.

ORIGINAL CURRICULUM

In Fall 1996, the primary design and manufacturing courses required within the ME curriculum were:

1. **MECH407:** Manufacturing Processes, an introduction to fabrication techniques,
2. **MECH392:** Mechanical Design, a focus on functional design and analysis, and
3. **MECH401–402:** Senior Capstone Design series, a full year design project that culminated in the fabrication and assembly of the final design (Fig. 1).

The Capstone design series was the only vehicle that allowed integration of lecture materials from MECH407 and MECH392. The laboratory portions of this three course series did not represent any logical progression or integration of knowledge due to a lack of any hands-on manufacturing experience in MECH407. The dedicated laboratory facility for all three courses was the college Computer-Aided-Engineering and Design (CAED) lab, composed of twenty-five Unix-based workstations. Although the specific purposes of MECH407 lectures were to teach basic manufacturing processes, the laboratory exercises focused on the computer aided design and analysis of parts, as in MECH302. As a result, students were missing a crucial component of the learning experience and often completed the course without a significant physical understanding and appreciation of fabrication techniques used in realizing an engineering design. Seniors entered the Capstone design series (MECH401/402) still unprepared to use the industrial size equipment available in the college Product Development Laboratory (PDL), requiring them to rely on college technicians and machinists for their project fabrication needs. In this form, the curriculum did not offer students any opportunity for the hands-on learning of manufacturing concepts, and did not properly prepare them for the complexities involved in designing and controlling a discrete part manufacturing system. The program also did not emphasize sufficiently the high degree of interdependency between manufacturing and design activities.

PLANNED IMPROVEMENTS

The curriculum was studied in detail with consideration given to various methods of enhancing the provided manufacturing education. This enabled the construction of a plan to improve the manufacturing curriculum within the bounds of departmental size, space, faculty, and curricular constraints. The main tasks planned over a four year period included changes and improvements to:

Facilities
- Develop a manufacturing processes facility to allow for hands-on student learning

Curriculum
- Incorporate and develop better tools to aid in the teaching of manufacturing processes
- Better integrate manufacturing and design within the curriculum, including design for manufacturability and concurrent engineering
- Distribute appropriate manufacturing concepts within other related courses

Research & industry involvement
- Develop a manufacturing research program and incorporate research into the classroom
- Develop partnerships with local industry in an effort to provide mutual benefits

The remaining sections of this paper describe some of these activities and the associated results.

FACILITY IMPROVEMENTS

The first priority was the goal of developing a manufacturing processes facility for instructional use. This effort received financial support from the National Science Foundation's (NSF) Instrumentation and Laboratory Improvement (ILI) program in Spring 1997 [DUE#9750788]. The result of this is the 'Integrated Manufacturing Processes Laboratory (IMPL)', a facility that enables students to get vital hands-on experience in conjunction with the study of manufacturing processes. There is also an emphasis on the integration of product fabrication and other key tasks in the development cycle. The equipment available in the facility includes computer-based machines capable of numerically controlled cutting

Table 1. Equipment in Integrated Manufacturing Processes Laboratory (IMPL).

Machine Type	Manufacturer & Model	Unit Cost*	Basic Process
CNC Milling Machines (3)	Light Machines Corp.: PLM1000	$18,000	Material Removal
CNC Lathes (2)	Light Machines Corp.: PLT3000	$17,000	Material Removal
Injection Molding Machine	Morgan Industries, Inc: G–100T	$15,000	Casting-polymer processing
Fused Deposition Modeler	Stratasys, Inc.: FDM2000	$120,000	Layered Manufacturing
Manual CMM	Brown & Sharpe: Gage 2000	$20,000	Quality Inspection

* Unit costs represent educational discounts.

operations, injection molding, layered manufacturing, and dimensional inspection (Table 1). Several machines are educational, as opposed to industrial-grade, sacrificing power and size capabilities for improved safety. This smaller scale manufacturing equipment allows for students personal involvement, gives them responsibility for part fabrication without lengthy machine training, and prepares them for the later use of industrial grade equipment in the PDL.

The Integrated Manufacturing Processes Laboratory became fully operational in Fall 1999, although portions of it began being incorporated into classes in Spring 1998. The equipment has served to fill the previously existing curricular void, providing the vital link between theory and application, and creating a more comprehensive and interesting learning environment. The facility does not function as a stand-alone facility for manufacturing courses, but as one integrated and associated with other departmental and college laboratories and classes. In this role, striving to emphasize the importance of communication and interaction between all functions of the product development cycle, the laboratory provides the necessary equipment to fabricate components in conjunction with activities in product design, prototyping, and quality inspection.

COURSE CURRICULUM

The ME department's manufacturing curriculum has changed in several ways over the past three years. The most obvious improvements have been:

- the use of the new manufacturing facility within existing courses;
- the development of a new elective course entitled MECH462: *Computer Aided Manufacturing.*

In addition to these changes, there was considerable effort placed on more subtle curricular adjustments to improve the teaching of manufacturing processes and to integrate manufacturing and design better.

Use of integrated manufacturing laboratory in existing courses

With the availability of necessary fabrication equipment, initial curricular enhancements included the development of manufacturing projects for incorporation within MECH407. The intention of the projects was to provide students with a hands-on experience in the computer aided design and manufacture (CAD/CAM) of a simple assembly. Initial MECH407 projects targeted the process of computer-numerically controlled (CNC) machining, with an emphasis on component assembly requirements and tolerances of fit.

Projects require the use of Pro/ENGINEER software for the first four laboratory sessions, comprising the CAD/CAM portion of the exercise. The generation of solid models for each component in a simple part, the creation of fully dimensioned and toleranced part specifications, and the verification of the feasibility of resulting component assembly were included in the CAD tasks. The CAM tasks include the placement/assembly of component models within solid models of planned raw stock, the generation of machine tool paths, and the simulation/verification of tool paths within Pro/MFG. Resulting cutter location files are post-processed into the machine language required by the ProLIGHT mills and lathes.

The next five laboratory sessions involve the physical fabrication and inspection of designed parts. Students are first given the opportunity to become familiar with the benchtop mills and lathes. They receive instruction on various techniques such as computerized code verification, local machine zero setup, and running machine code at a z-value above the actual stock. Students are then responsible for the workholding and machining of each of their components. There is inspection of critical features and assessment of dimensional quality. The completion of successful projects includes part assembly and finishing. Timing of these laboratory exercises is in conjunction with lecture material intended to assist students with the various tasks, such as defining feasible design tolerances, computing appropriate machine parameters such as spindle speed and feed rate, selecting tool geometry (Table 2).

Figure 2 presents a sample student project entitled 'Tee Time'. Student responsibilities included:

- solid modeling of the golf ball, the tee, and the octagonal base;
- computer-aided assembly verification and calculation of tolerances of fit between ball and tee, and between tee and base;
- generation of associated design specifications;

Table 2. Laboratory activities in MECH407.

LAB TOPIC	FACILITY	Software/Equipment	LECTURE TOPIC
Solid Modeling	CAED (1)	Pro/ENGINEER	CAD
Assembly models & Drawings	CAED (1)	Pro/ENGINEER	GD&T
Manufacturing models	CAED (2)	Pro/ENGINEER	CAM
CNC machining demo & tutorial	IMPL (1)	CNC mills & lathes	Cutting Processes
Student machining	IMPL (2)	CNC mills & lathes	Cutting Processes
Quality Inspection	IMPL (1)	CMM	Inspection/Process Control
Assembly & Part finishing	IMPL (1)		Joining/Finishing Processes

- computer-aided tool path generation for material removal on all three components;
- CNC milling and drilling of octagonal base and golf ball;
- CNC turning of golf tee;
- dimensional inspection of features involved in tee-base placement;
- physical assembly and finishing.

Although MECH407 still includes several industrial field trips and in-house processing demonstrations, this hands-on fabrication project dominates the laboratory experience and successfully replaces the once passive learning environment. This transition establishes a pedagogical goal for students: to develop a genuine understanding of the problems, limitations, and benefits associated with various manufacturing processes. This has included an understanding of:

- the specifics of the process and the associated material effects;
- its viability as an option for the fabrication of a given design, including a formal awareness of design for manufacturability (DFM) issues;
- its role and position in the product realization process.

Through the course of the project students are also required to identify tools for solving any problems that may arise.

Once completed, students are able to fabricate many of their own components in the Capstone design course. Experience has shown that these activities help develop student awareness of some common stumbling blocks in fabricating a design. This comprehension helps improve the quality of many Capstone design projects, rendering students more careful with their own designs, and more capable to assess the processing ramifications of design decisions and the feasibility of manufacture.

Computer-aided manufacturing elective

Computer-integrated manufacturing is a broad term used to describe the computerized integration of all aspects of design, planning, manufacturing, distribution, and management [4]. If successful, the benefits of this computerized integration include:

1. responsiveness to shorter product life cycles, changing markets, and global competition,
2. emphasis on product quality and uniformity through better process control,
3. improved process efficiency and productivity, and
4. better control of operation resulting in lower cost.

The effectiveness, however, depends largely on integrated communication systems involving computers, machines, and their controls [5].

MECH462: Computer Aided Manufacturing (CAM), offered for the first time in Spring 1999, focuses on the computerized integration specific to design and manufacture. The course begins with an in-depth look at solid modeling and CAD as the major key to integrated information in manufacturing systems, offering a more advanced look at CAD and CAM than that offered in MECH407. It builds upon the students general knowledge of CAD applications obtained in prerequisite courses, and provides them with a deeper understanding of geometric modeling, basic computer graphics, feature modeling, and associated database issues. They are then able to use this information to explore a variety of manufacturing concepts and techniques in both lecture and laboratory, focusing on their related computer-aided and integrated applications. Primary topics are:

1. Communication and exchange of data between varying design and manufacturing systems.
2. Computer-aided processing, rapid prototyping, and inspection.
3. Computer-aided process planning (CAPP), focusing on the selection of production methods, tooling, fixturing and machinery, operation sequencing, and assembly.

The CAPP unit includes the direct integration of ongoing research projects in computer aided planning of dimensional inspection and layered manufacturing processes.

The laboratory portion of the class uses the processing machines in the IMPL and Pro/ENGINEER software modules as provided through the CAED laboratory. Students first complete a series of four laboratory exercises intended to familiarize them with certain concepts, equipment, and software beyond the scope of MECH407 (Table 3). After this, the students use the remaining eight weeks of laboratory sessions for the development and completion of a CAD/CAM project of their choice. The expectation is that course projects will

Fig. 2. MECH407 project: 'Tee-Time': (a) Solid models of main parts; (b) Machined parts and clock; (c) Final product.

Table 3. Preliminary laboratory activities in MECH462.

LAB TOPIC	Software/Equipment	LECTURE TOPIC
Solid Modeling	Pro/ENGINEER	CAD & Data Representations
Injection Molding	Morgan Industries: G–100T Press	Mold design & DFM issues
Inspection & Reverse Engineering	Brown & Sharpe: Gage2000	Inspection/Process Control
Layered Manufacturing	Stratasys: FDM2000	Rapid Prototyping

include the usage of a minimum of three different processing types as available in the IMPL, including:

- material removal (milling and turning);
- internal flow (injection molding);
- layered manufacturing (FDM);
- quality inspection on the CMM.

The primary objective is to integrate CAD and CAM in the design and fabrication of a product, offering a more advanced experience in information flow between design and manufacture.

Figure 3 presents a sample student project that resulted in the fabrication of a plastic medallion bearing an image of Bucknell's Bertrand Library [6]. Student responsibilities included:

- digitization of library image;
- image processes from wireframe, to surface, to solid model of planned medallion;

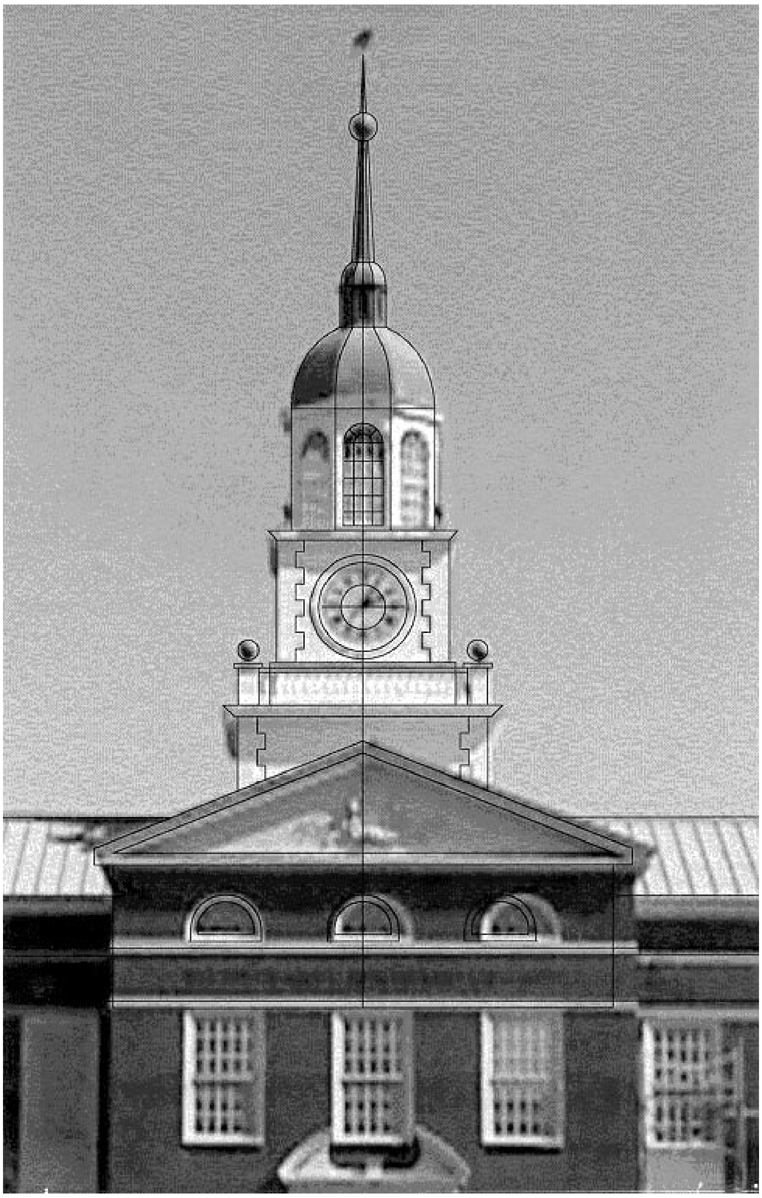

Fig. 3. MECH462 project: (a) Digital photo of Bertrand Library; (b) Solid model of injection molded medallion.

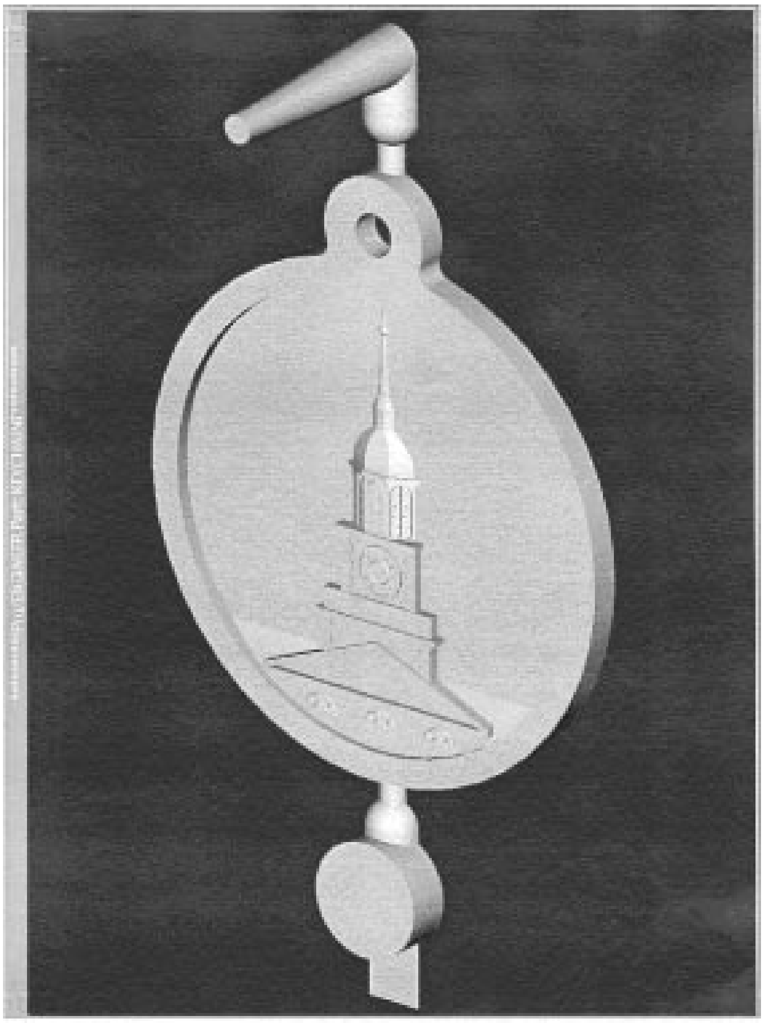

Fig. 3. *Continued*

- solid modeling of inverted image and die set for injection molding machine;
- generation of associated design specifications;
- computer-aided tool path generation for material removal on die set;
- CNC milling of dies, included mold cavities, sprues, runners, and threaded holes required for die installation;
- mold inspection & finishing;
- injection molding of thermoplastic medallion;
- sprue and runner removal and part finishing.

Improved practices within existing courses

As well as these changes, there has been considerable effort placed on smaller curricular adjustments to improve the teaching of manufacturing processes and to integrate manufacturing and design education better. In Fall 1996, sufficient funding became available to provide the ME department with affiliate status within the Product Realization Consortium [7]. The consortium is a group of five schools, funded in conjunction with a National Science Foundation Cooperative Agreement (DMI–9412089), focused on initiating a systematic reform of engineering education specific to the presentation of the product realization process within undergraduate curriculums. The affiliate award enabled MECH407 students to participate in the beta-testing of multimedia modular courseware developed to address key issues in integrated manufacturing. The test included a laboratory session based on the use of OPTLINE, a computerized manufacturing system model that simulates the production of a simple part using casting, drilling, and turning [8]. OPTLINE assists students to understand the connection between the physical and economic design of manufacturing processes, and to demonstrate the direct effect of fabrication decisions on other upstream processes. Many students showed amazement at their observations of the impact of their various process variable decisions. According to their evaluation forms and related feedback, this exercise served successfully to solidify many concepts addressed throughout the semester, and use of the OPTLINE software continues in the laboratory portion of MECH407.

In the Fall of 1997, collaboration with Cornell University's Product REALIZATION team enabled further examination of these topics. This project included the development of second phase modular courseware and computerized models used in teaching the concepts of a systems approach to design and manufacture to undergraduates. The author was involved in developing models and lecture material for test by consortium affiliates through web-based dissemination [9]. Enhancement and incorporation of these materials within MECH 407 continues.

In additional efforts to distribute manufacturing topics within college-wide programs, the ME department continues to participate in Bucknell's 'Institute for Leadership in Technology and Management (ILTM)' program. Providing a six week summer experience to selected juniors in management and engineering departments, the department is responsible for several technical presentations and demonstrations related to manufacturing systems, design, and robotics. Presentations have included sessions on:

1. 'An Introduction to Manufacturing Processes', including demonstrations on machining CNC machining, injection molding, fused deposition modeling, and robotics.
2. 'World Class Manufacturing: Improving the Process of Product Realization', representing a higher level look at issues affecting global competitiveness.

Another effort focused on the integration of manufacturing and design within the curriculum has been the development and inclusion of multimedia course material on geometric and dimensional tolerancing (GD&T) concepts and practices. There is now a GD&T unit included within MECH407, in conjunction with discussion on process capability. The students are introduced to the related ANSI standard and are required to complete various activities focused on proper interpretation of defined geometric tolerances. There is further enhancement of this topic using videos, and various experiments that make use of the manual CMM within the IMPL.

SMALL BUSINESS DEVELOPMENT CENTER

At Bucknell, there is a unique university/industry partnership with the local Small Business Development Center (SBDC), that helps to sustain a high quality manufacturing program and associated facilities. The SBDC, located within Bucknell's Dana Engineering building, provides managerial and engineering business development consultation to small businesses in a six-county region. Financed by the US Small Business Administration, the Commonwealth of Pennsylvania, the Ben Franklin Partnership Program, and the university, Bucknell's SBDC is the only one in the state that includes a Product Development Center (PDC). To assist the Commonwealth's inventors and small firms in transforming their ideas into products, the PDC provides assistance in various types of projects including product design and/or redesign, prototype development, product testing, feasibility and manufacturability analyses, process improvements, and preliminary patent searching.

The PDC requires engineering consultants, expertise and advanced manufacturing facilities to serve best in this role. Bucknell faculty serve as technical consultants, and engineering students often become involved through the Capstone design course. This relationship provides students with real-world product development projects, and offers them the opportunity to collaborate with actual clients. This aspect of the relationship between industry and academia has proven successful for several years.

In the past few years, however, an additional benefit has evolved through this partnership. The SBDC director and the author have worked together to obtain relatively expensive processing equipment intended to benefit both the academic mission of the manufacturing program and the service mission of the SBDC. One instance was the purchase of the layered manufacturing machine, FDM2000. Although partially funded through NSF grants, SBDC and the Ben Franklin Partnership Program also provided additional funding.. Another example is the recently ordered computer-controlled coordinate measuring machine (CMM). This piece of equipment should enhance the college's measuring and quality inspection facilities, as well as provide enhanced reverse engineering capabilities.

The bi-directional information flow between the college and local industry partners offers the students a unique opportunity to apply engineering problem solving skills to real world scenarios before graduation. Recent product development projects have been in the areas of: material handling and manufacturability improvements [10], design feasibility and strength testing, product performance testing, and product design and/or redesign.

MANUFACTURING RESEARCH

Research is critical in providing long-range capabilities of the manufacturing industry, and is a vital ingredient in any manufacturing education program. With the SBDC partnership serving to provide students with applied industry-specific projects, the goal was to work towards developing a basic research program in one or more areas of manufacturing. Consideration of this objective was with respect to the following programmatic constraints:

- the highest terminal degree offered in the college of engineering is a Master of Science;
- the limitations of faculty experience and expertise.

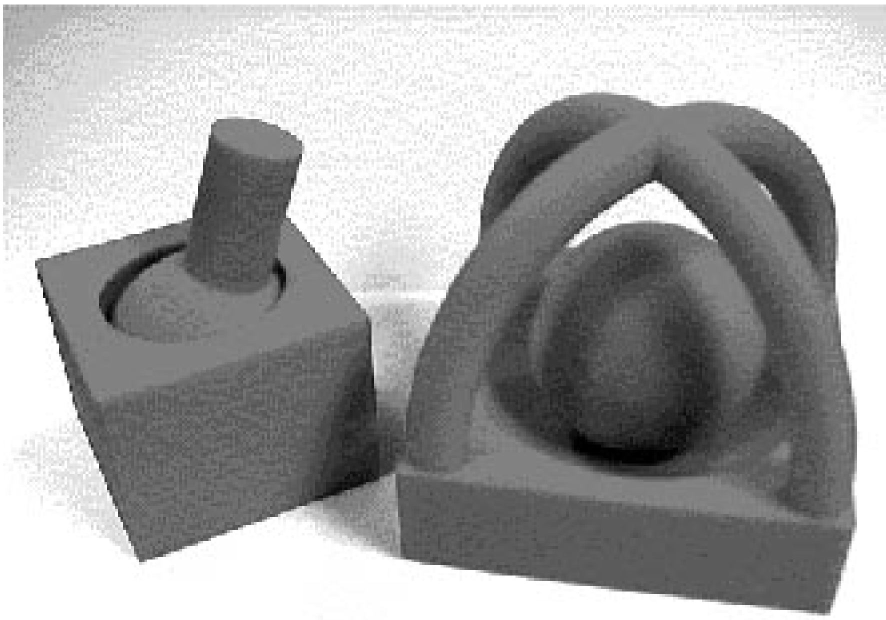

Fig. 4. Two parts fabricated for senior design project entitled 'Single-step FDM fabrication of Assemblies'.

The effort towards developing a basic research program received initial financial support from NSF [#9813042] for a project intended to develop a methodology for the computer aided decision support and design feedback associated with the Fused Deposition Modeling process (FDM). The overall project goal is to provide the knowledge and the means by which the design engineer is able to make manufacturing and prototyping decisions. This system will serve to improve the interface between the design and the manufacture of FDM parts, and to provide important evaluation capabilities for design feedback. The project is working towards providing these enhancements with a special focus on the needs of small business manufacturers, who by nature suffer from the limitations of a smaller work force.

Project objectives include:

1. FDM experimentation and process modeling,
2. the development of computational tools to optimize the FDM process based on the design specifications and feature requirements;
3. the implementation of associated algorithms and models to provide predictive capabilities and decision support for designers and FDM users.

The focus of the objectives is to provide a more seamless design and/or fabrication interface and to improve the quality of the freeform fabrication process specific to functional design requirements of key part features. Demonstration and validation of the decision support system will make use of industry data provided through SBDC collaboration with local manufacturers.

Further enhancement of this research occurs through additional funding from the Ben Franklin Partnership Program [11], and Ziemian and Crawn [12, 13] documented the accomplishments to date. If successful, the research will serve to provide time-saving tools which facilitate the rapid identification of design possibilities and the early integration of manufacturing considerations. The developed methodology will highlight the important elements in manufacturability assessment, and demonstrate the possibility of linking back to the product model in investigating redesign options. Improved decision support and assessment capabilities will also serve to promote the further use and industry approval of layered manufacturing methods as more than a rapid prototyping technique.

Less tangible benefits have included the educational impact on graduate and undergraduate students in the ME department. Elective course MECH462 now includes related process planning techniques specific to the FDM process. A new laboratory experiment recently designed presents the benefits of the developing decision support system over the unskilled machine operation of the FDM machine. Capstone design projects that include a process planning exercise specific to the single-step fabrication of engineering assemblies (Fig. 4) have focused on related use of the FDM2000.

CONCLUSIONS AND RECOMMENDATIONS

Implementation of the current design and manufacturing curriculum, (as presented in Fig. 5), occurred during Spring 1999. Achievement of the primary objective of improved manufacturing education occurred in various ways, such as by using funding and resources from assorted sources.

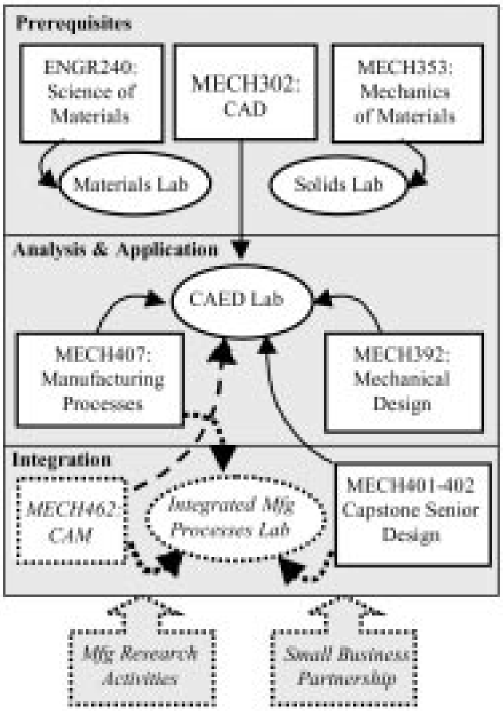

Fig. 5. Current ME design/manufacturing curriculum (with recent additions identified by dashed lines).

The students now receive introduction to manufacturing processes together with concerns relating to design for manufacturability. There is now lecture and laboratory emphasis on the affect of manufacturing issues on product design. Students now experience the integration of different engineering tasks in practicing concurrent engineering techniques. There is emphasis on teamwork and communication skills throughout all project activities. Student feedback has become more positive with each new addition of a hands-on exercise and/or project.

The main problems and obstacles experienced to date relate to equipment and software bugs, and software licensing issues. The high quality technical support available within the ME department continues to strengthen the integrated manufacturing effort. Overemphasis of the importance of such technical support and related training is not possible [14]. Successes to date would not have been possible without this qualified assistance, and the coordinated teamwork between ME faculty and technical support personnel.

There is still much room for further improvement. Completion of the installation of the IMPL equipment has now enabled the author to consider ways to offer additional MECH407 lab experiences. Currently the primary MECH407 student project is the previously described CNC machining experience. The goal is now to develop a rotating lab schedule that would allow some students to make use of the FDM machine, while others are using the injection molding machine, and still other are on the benchtop cutting machines. The idea would be that the students would complete their projects at the same time and then rotate to the next machine after about one-third of the semester, providing about five weeks per project. The equipment is in place for such a plan, but there is a need for more work to consider the proper integration of lecture topics and lab experiences. There is a further need for detailed consideration of the technical support of such a rotating lab system.

Another possible enhancement to such a rotating MECH407 lab schedule is to offer a list of four or five lab projects, from which each student would have to select three. The goal would be that the class as a whole cover all five projects, although each student would only receive the hands-on experience with three processes. Then introduction to the difficulties and successes associated with each project would be through student presentations to the entire class. This scenario might also allow room for a project focused on the downstream process of mechanical testing. Tensile, compression, and fatigue testing on fabricated parts would serve to demonstrate the different effects of both processing type and material type, and fill a current void in the existing lab outline.

Further work is also necessary to distribute manufacturing concepts throughout other ME courses. First, this would better emphasize crucial topics and assist in student learning. For instance, experience has shown that the single GD&T unit within MECH407 is not sufficient to prepare students to interpret the many possible geometric tolerance callouts properly. There should be consideration given to additionally incorporating these important concepts within other related courses, such as MECH302 and the Capstone design course. Second, this would provide more room within MECH407 to cover the vast variety of important processing techniques in a better way. There could be further consideration given concerning the incorporation of a manufacturing laboratory exercise within other required courses. For example, an exercise on the plastic deformation of materials would fit within the objectives of MECH353: Mechanics of Materials, and could serve as an introduction to forging processes. By better integrating some manufacturing topics within other design and related courses, MECH407 could more successfully introduce traditional processing methods, as well as new and emerging fabrication methods.

Traditional interdisciplinary boundaries are a key obstacle [15] that still needs consideration to achieve true innovation in Bucknell's manufacturing education. Coordination of related efforts across the departments of chemical, electrical, and civil engineering would greatly enhance the quality of the manufacturing education within the college, and better allow for multidisciplinary teamwork. Similarly, coordination between

Capstone design projects and related projects within the Management department may be another potential avenue towards multidisciplinary team formation. Interdepartmental collaboration is perhaps the most important area requiring effort towards the continued improvement of Bucknell's manufacturing education program.

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