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Adapting Learning Factory Concepts Towards Integrated Manufacturing Education*

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The Learning Factory (LF) concept integrates a practice-based engineering curriculum that strives to balance analytical and theoretical knowledge with learning enhancements through hands-on fabrication experiences. We have completed a project based on adapting key components of the original LF model, strategically expanding manufacturing-related education within a small mechanical engineering department. The implementation includes equipment installation, development of hands-on learning opportunities in materials processing and inspection, strategic formation of a lab infrastructure that creates course linkages and provides complementary coverage of fabrication principles within core courses, the integration of manufacturing research and education and the implementation of K–12 outreach activities.

Keywords: Active learning; manufacturing equipment; laboratory development; educational modules

INTRODUCTION

MANUFACTURING INDUSTRIES WORLDWIDE have undergone dramatic changes in recent years as a result of the effects of industrial globalization. One obvious impact has been the outsourcing of manufacturing by US companies in efforts to keep products competitive in the global market. These trends, currently redefining the manufacturing enterprise, now serve as motivators for change in academia. Engineering educators are challenged to evolve the systems and curricula used to provide students with improved manufacturing education, including discipline-specific fundamentals and multidisciplinary knowledge and skills [1].

American industry is alert to the importance of the manufacturing enterprise and the need for effective education. Their expectations of new engineers are changing with the recognition of the need for new skills to function effectively in an environment characterized by aggressive global competition and rapid changes in materials processing and related technologies [2]. Manufacturing and industrial engineering departments have begun to address these needs with the development of new courses, majors and educational tracks [3, 4]. Academic programme change in other engineering departments, however, has been much slower. Of specific interest here is the need for innovative methods of improving manufacturing education within mechanical engineering departments.

Significant system and curricular change related to improved manufacturing education within mechanical engineering departments is more difficult in part because it is easier for faculty to teach what they were taught when they were in school. Radical changes in curricula often meet with resistance among established faculty. Opposition to change may be further fuelled by the criteria published by the undergraduate Accreditation Board for Engineering and Technology (ABET). While ABET standards for manufacturing engineering delineate between distinct areas of importance including materials processing, production systems, competitiveness and manufacturing integration, ABET criteria for mechanical engineering contain no requirements for manufacturing-related topics [5]. Consequently, an educational response to evolving technologies or industry needs might require the hire of faculty with interests or expertise in these new areas.

Even if the need for change is supported, and qualified faculty are interested and available, efforts to advance manufacturing education are more constrained within mechanical engineering departments. Most often, these programmes are more successful at integrating aspects of manufacturing in their graduate curriculum or as upper-level electives. At the undergraduate level, however, it is much more difficult for a mechanical engineering curriculum to stretch its course capacity to include a comprehensive range of manufacturing principles and applications [1]. It is not uncommon for such a department to have only a single course dedicated to manufacturing education. To make the stretch, therefore, requires a rethinking of traditional core subjects and applications.

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An innovative curricular change of this kind is described in this paper. It includes the development of a physical laboratory facility and its role in improving the quality of the manufacturing education and the integration of manufacturing topics within a structured and traditional mechanical engineering curriculum. The facility represents an adaptation of the Learning Factory model originally developed at Penn State University, and the Universities of Washington and Puerto Rico-Mayaguez [6]. It serves to emphasize learning enhancements through practical hands-on experiences. Important curricular changes towards improvement have included the reordering of courses within the undergraduate sequence, the addition of hands-on fabrication activities, experiments, and projects, the inclusion of manufacturing topics, case studies and modules within other mechanical engineering courses, the integration and coordination of these topics across courses and the addition of new electives. Preliminary assessment results indicate that these modifications have had a positive impact on the educational programme.

BACKGROUND

The Mechanical Engineering department at Bucknell University is the only department in the College of Engineering requiring a full manufacturing course, i.e. MECH355: *Manufacturing Processes*. Before 1997, MECH355 was without any hands-on fabrication opportunities for the students. Because fabrication processes are often complex and require an understanding of theories related to strength of materials, heat transfer, materials structure etc., the implementation of lab sessions is vitally important. Efforts to address this educational void were initially sparked by funding from the National Science Foundation's Instructional Laboratory Improvement (NSF-ILI) programme in 1998. This award enabled the purchase of several low power benchtop processing machines, representing the preliminary step towards introducing hands-on activities in MECH355. Seeded by the educational success of the NSF-ILI project, additional funds were obtained to duplicate, upgrade and supplement the machines until the manufacturing laboratory eventually reached its Phase I stage in Autumn 2002 (Table 1). In this form, the equipment included educational and tabletop models that sacrificed power for improved safety and minimal space demand [7].

Although the equipment offered the opportunity for an educational link between theory and application in MECH355, there were problems associated with the quality of machine tools and the type of processes represented in the laboratory. The CNC cutting machines were small benchtop models with limited power. As a result, they were not capable of cutting metals efficiently, and student machining projects were restricted to plastic prototypes. Although this is arguably a meaningful educational experience, it limited the impact of the laboratory projects in several significant ways. First, the students were not able to easily make the connection between theory and practice as the majority of available machining tables are designed for the cutting of metals. Even with the proper table data, theoretically determined cutting speeds frequently had to be reduced to avoid excessive vibrations of the small machines. Second, the limited power and the reduced speeds and feeds served to increase the amount of time needed for the completion of a single project. This made the completion of more detailed and realistic projects too time consuming. As a result, projects were forced to be simplistic in order to allow each student to experience the hands-on opportunity. Additionally, each student was forced to select to participate in either a milling project or one using the lathe. Time constraints would not allow each student to complete both. Lastly, the plastic parts generated on the CNC machines only served the role of prototypes. They did not lend themselves to further processing. For instance, faculty desired to integrate the milling project with an injection moulding experience by machining moulds. This was not feasible without the ability to cut metal.

In general, these problems detracted from the goal of exposing students to industrial practices. In addition, the materials processing education was not diverse, and there was little lab time remaining for the inclusion of additional hands-on activities with available equipment (Table 1). These shortcomings further restricted the ability to integrate manufacturing and design as student familiarity with the benchtops could rarely be used in capstone design projects (which more often required the cutting of metal). Lastly, the equipment offered limited possibilities for effective collaborative lab experiments/projects between MECH355 and related core courses.

Table 1. Phase I manufacturing laboratory

Machine type	Manufacturer and model	Basic process
Benchtop CNC Mills (2)	Light Machines Corp: *PLM1000*	Material Removal
Benchtop CNC Lathes (2)	Light Machines Corp: *PLT3000*	Material Removal
Injection Molding Press	Morgan Industries, Inc., *G100T*	Casting-polymers
3D-Printer	Z-Corp: *Z400*	Layered Manufacturing
Manual CMM	Brown & Sharpe: *Gage2000*	Quality Inspection

Fig. 1. Manufacturing related curriculum in 2002–03.

In addition to the physical restrictions of the equipment, the structure of the curriculum presented another obstacle in striving to improve the manufacturing education. Without the benefit of an industrial engineering or manufacturing department, efforts to integrate manufacturing courses and topics throughout the curriculum are uniquely constrained. There is a finite amount of course material that can be covered within the single manufacturing class (MECH355). Any secondary coverage of related material must occur strategically in other courses. As seen in Fig. 1, the courses most directly related to manufacturing topics were sequenced in such a way that this was not possible. The most significant shortcoming of this course progression was the fact that MECH355 was not offered to the students until their senior year. This disabled the course from serving as prerequisite material for design classes, severely limiting the possibility of secondary coverage of manufacturing topics in other core courses, and restricting the opportunity for advanced manufacturing-related elective courses for undergraduates.

In this form, the curriculum did not facilitate the integration of manufacturing and materials processing concepts and equipment within related core courses. Without practice-based linkages, students were often unable to recognize the important connections between related topics and the high degree of interdependency between manufacturing and design activities.

PROJECT IMPROVEMENTS

A small group of faculty within the mechanical engineering department recognized the significance of these shortcomings and defined a strategy to further improve the manufacturing curriculum within the bounds of departmental size, space and curricular constraints. Project plans were proposed to NSF's Course Curriculum and Laboratory Improvement (CCLI) programme, and were funded in 2004. This project focused on increasing the value of the learning experience offered in the single, dedicated manufacturing course (MECH355), and better integrating hands-on manufacturing education throughout related core courses, subsequent design activities, new electives and undergraduate research projects [8]. The desired outcome was a more practice-based curriculum that would assist students in developing the skills needed to integrate manufacturing and design in real-life product realization projects. The plan to achieve this outcome was based on an adaptation and implementation of the Learning Factory model developed at Penn State University, and the Universities of Washington and Puerto Rico-Mayaguez [9].

The Learning Factory (LF) model calls for an on-demand laboratory containing the manufacturing equipment necessary to complete product realization projects in practice-based curricula that integrate design, manufacturing, and business realities. It recognizes the need for both intellectual and physical activities to anchor the knowledge and practice of engineering in the minds of students [10]. The initial LF model was developed to address the limitations of a purely lecture-based education. Based on the demonstrated effectiveness of augmenting lecture with laboratory experiments and hands-on activities, the LF was originally developed as a facility to be used across the curriculum, analogous to the way one might use a library.

The NSF-CCLI project implements the LF philosophy while adapting it to a small engineering college that, unlike the original model, is without an industrial engineering department and has product design and analysis as its primary focus. The LF concept has been modified in scale and application, offering product realization equipment directly to MECH355 and subsequent Capstone design projects (MECH401/402), and providing improved facilities needed to integrate manufacturing topics into related engineering core courses. The intent has been to create the LF as a place where faculty can bring classes for hands-on activities, experiments and real life applications of topics discussed in lecture.

The primary project goals include:

1. Increased quantity and variety of hands-on manufacturing learning opportunities.
2. Curricular realignment to allow for the incorporation of manufacturing topics within related engineering core courses and the improved integration of design and manufacturing education.
3. Development of new course modules, elective courses, research projects and K–12 outreach activities.

HANDS-ON LEARNING OPPORTUNITIES

A combined hands-on and experimental approach is an effective way to enhance student

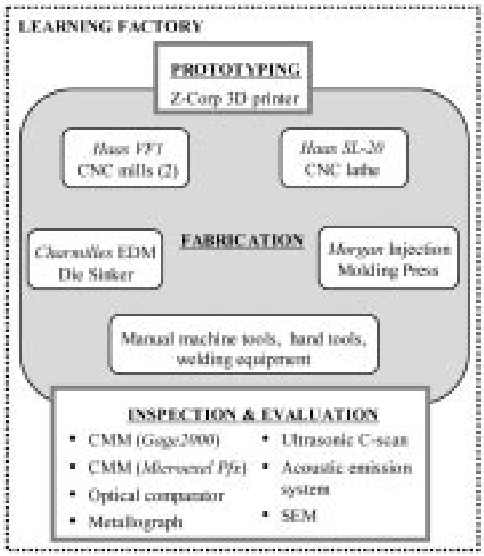


Fig. 2. Manufacturing facilities available Autumn 2006.

comprehension of materials processing and manufacturing principles. The LF model has demonstrated the success of a more practice-based curriculum that balances analytical and theoretical knowledge with manufacturing and design skills [10]. As a result, project plans have focused on the importance of increasing the opportunities for students to learn by experience, to apply theoretical manufacturing principles to the physical world and to develop an appreciation for the complexities of processing engineering materials into finished products.

Improved coverage of a variety of major manufacturing processes and engineering materials through hands-on activities required enhanced fabrication facilities and restructured MECH355 lab activities. The new manufacturing equipment (Fig. 2), funded in part by the National Science Foundation and the Department of Energy, provides several important advantages over the previous MECH355 laboratory. The low-powered benchtop CNC machines were replaced with industrial-size CNC equipment, allowing for the following improvements:

- Efficient cutting of a variety of engineering materials including metals, polymers, wood, etc.
- More direct application of the theory learned in class, i.e. mechanics of chip formation, calculation of recommended speeds and feeds, methods for improving surface finish, etc.
- Machining of metal mould cavities to be subsequently used in injection moulding of thermoplastics; better integration of processes and ability to incorporate injection moulding into project experience.
- Faster machining of individual project, allowing more time for additional hands-on opportunities.

In addition to the improved CNC machines, new equipment has allowed for the introduction of technologies previously unavailable within the lab. Electrical Discharge Machining (EDM), for instance, is now studied in some detail in MECH355. Students are introduced to different types of EDM processes and related issues such as equipment, process parameters, flushing techniques, electrode materials and electrode wear. The new EDM die-sinker is incorporated into the laboratory portion of MECH355 as a demonstration of cutting hard metals and cutting very thin pieces of material, as well as a means with which to quickly and efficiently engrave student projects. The value of this experience is accentuated by the fact that students had already cut their products on the CNC machines and have learned first-hand about the depth of cut and feed limitations of cutting with small diameter end mills and engraving tools. Consequently, they are able to appreciate the relatively fast EDM engraving of thin, detailed letters and features, and better understand the differences between EDM and traditional mechanical cutting processes.

Non-destructive testing (NDT) equipment is also now available to use in conjunction with materials processing education. NDT is a very broad and interdisciplinary field that is based on locating and characterizing material and flaws that might otherwise cause products to fail. This equipment is very useful in teaching students how fabrication and specific processing methods contribute to the microstructural character of particular materials. General issues regarding process-material interaction and the resulting product quality and material integrity are important aspects of a manufacturing education. These topics compose the final module of the MECH355 course, and are meant to represent an introduction to inspection and evaluation as a means of analysing process capability and effectiveness. For example, the effect of EDM process parameters on resulting surface integrity is a meaningful investigation made possible with the availability of the new EDM die-sinker and the NDT equipment.

The LF equipment has already proved useful for demonstrations and experiments during class time and has provided much needed time and capacity for a total restructuring of the MECH355 laboratory semester. The MECH355 lab now offers substantially increased and improved hands-on processing opportunities. The syllabus (Table 2) includes several additional manufacturing processes in hands-on projects, compared to the previous situation where each student was able to complete only a turning or a milling project and a rapid prototyping project. These projects are individualized by each student as they are encouraged to explore and integrate, rather than follow a defined step-by-step procedure to create a required product. The objective of each fabrication project is to develop an understanding of the process capability and its limitations and benefits, rather than to train the students to master machine operation.

Table 2. Structure of new MECH355 Laboratory Activities (single semester)

MECH355: Hands-on laboratory activities covered by each student	
1	Rapid Prototyping—3D Printing
	Create solid model (Pro/ENGINEER) of desired part; Post-process to STL format;
	Complete training on 3D printer; Send STL file to printer and generate prototype;
2	CAD/CAM Project—CNC Machining
	Create solid model of: (a) part to be cut on lathe, and (b) part to be injection molded;
	Create solid mold for part (b) using cut-out modeling procedure;
	Complete CAM software (Pro/NC) tutorial; Use Pro/NC to generate cutter tool paths;
	Complete hardware and software training on CNC lathe and mill;
	Send NC programs to controller software and verify/debug;
	(a) Machining of LATHE project, i.e. Clock stand, cup, candleholder, etc.
	(b) Machining of MILL Projects, i.e. Molds for injection molded coaster, key chain, etc.
3	Electrical Discharge Machining (EDM)
	Complete training on EDM die-sink machine; Use machine to engrave product 2(a);
4	Polymer Processing—Injection Molding
	Complete training on injection molding machine; Cast multiple parts using mold from 2(b);
5	Quality Inspection/ Metrology
	Complete training on CMM; Inspect a critical feature of one of the lab products;
	Inspect a critical feature on one of the lab products using CMM;
	Complete an error analysis based on comparison of measurements & original design;

One popular project choice is the CNC machining of an aluminum mould for the production of custom beverage coasters. The process includes the following steps:

1. Design a coaster;
2. Create a solid model of the coaster (Fig. 3a);
3. Create a solid model of the mould;
4. Generate the CAM tool paths needed to machine the mould (Fig. 3b);
5. Post-process the tool paths to create an NC program;
6. Machine the aluminum mould;
7. Produce a set of coasters on the injection moulding machine.

A common turning project on the CNC lathe includes the design and machining of an axisymmetrical clock base. Figure 4a includes a student's golf-tee base assembled with a golf ball and clock face. Figure 4b displays the engraving on the clock base as completed by the EDM die sinker.

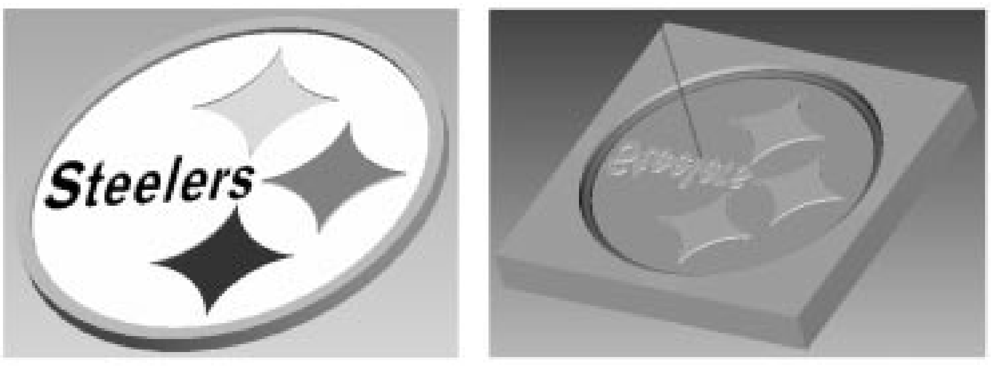
CURRICULAR REALIGNMENT AND IMPROVED INTEGRATION

With only a single course in the mechanical engineering curriculum dedicated to manufacturing, improved coverage of the many pertinent and related topics requires coordination with other core courses. The first requirement for this improvement was the rearranging of affected courses. This curricular adjustment was completed for the 2005–06 academic year. Most important was the shift of MECH355 from the first semester of the senior year to the first semester of the junior year (Fig. 5).

With the help of this course sequence change, efforts have been successfully implemented to better integrate manufacturing education throughout the mechanical engineering curriculum. The key changes and resulting benefits are listed below.

Complementary coverage of manufacturing principles

The complementary coverage of fundamental manufacturing principles has been implemented



(a) (b)

Fig. 3(a). Solid model of a beverage coaster; (b) CAM verification of tool paths on associated mould.

(a) (b)

Fig. 4(a). Golf-tee clock base created on lathe; (b) EDM engraved lettering on clock base.

Fig. 5. Sequence of manufacturing related courses 2005–06.

within related core courses. This coverage has included course material as well as hands-on learning opportunities. Laboratory activities have been created and coordinated to allow for the simultaneous coverage of manufacturing topics within courses taken concurrently. The developed 'linkage labs' integrate fabrication topics and projects with principles being concurrently covered in MECH353: Solid Mechanics and MECH313: Fluid Dynamics. For example, the MECH355 analysis of bulk deformation processes, such as open die forging, is timed with the MECH353 lab coverage of compressive failure, ranging from yielding or barrelling to buckling. Similarly, the MECH355 module on polymer processes and the injection molding of student projects in the laboratory are timed with the MECH313 Computational Fluid Dynamics (CFD) module and related software used to analyse the flow of a polymer through a mould. These linkage activities (Table 3) serve to reinforce manufacturing concepts in alternate courses and settings, further emphasizing the connectivity of fundamental concepts in a typical manufacturing system.

Manufacturing vocabulary usage

While the described linkage labs affect only those courses that are taken concurrently with MECH355, similar efforts have been made to increase the awareness of manufacturing by presenting materials processing applications as examples within traditional courses. In some cases, this has been as simple as using manufacturing vocabulary within other courses. Such efforts appear beneficial even in courses taken before MECH355. For instance, in the sophomore level *Dynamics* class (MECH252), the authors successfully analyse:

1. a gravity-drop forging hammer, in the study of work and energy methods;
2. a knuckle-joint forging press, in the study of kinematics and mechanisms;

Table 3. Linkage labs and complementary hands-on coverage of manufacturing topics

MECH355 Topic	Secondary Coverage
CLASS: Deformation processes, i.e. Forging, Rolling, Extrusion	MECH353 (Solid Mechanics): Lab exercises analyzing yielding (barreling) under compression, including buckling;
CLASS: Machining processes and mechanics of chip formation; LAB: CNC projects on mill and lathe	MECH353 (Solid Mechanics): Large shear strain—calculation using mechanics of chip formation
CLASS: Nondestructive evaluation of the processing effects on materials	MECH353 (Solid Mechanics): NDT lab; Determination of σ & ϵ via photoelasticity;
CLASS: Polymer processing and injection molding process; LAB: Injection molding of thermoplastic product using CNC-machined mold	MECH313 (Fluid Dynamics): CFD software used to analyze flow of polymer into student designed mold

3. an end-mill spinning on a machine spindle, in the study of fixed-axis rotation.

These examples have sparked student interest and often result in further discussion and analysis of the manufacturing situation, i.e. is the primary processing goal to maximize the work done per hammer blow when open-die forging a billet? Similar examples are easily integrated into other courses, such as heat transfer applications that include mould design for metal casting and material science applications that analyse the heat affected zone of a weld, etc. The main issue and potential obstacle is faculty interest and motivation.

Materials processing as a prerequisite for design

Concurrent engineering practices have long emphasized the need to simultaneously consider design and manufacturing requirements to reduce costs and lead time, and to improve product quality [11]. The mutual dependencies of all phases of the product realization process require related topics to be considered in parallel. The LF equipment available for hands-on experiences in manufacturing and product realization has helped emphasize these dependencies. Additionally, the shift of MECH355 to the first semester of the junior year has allowed the materials processing education to serve as prerequisite material for departmental design classes.

As shown in Fig. 5, Mechanical Design and Senior Capstone Projects now follow MECH355 in the course series. Students now obtain materials processing education and physical fabrication experience in MECH355, both of which increase the value of their subsequent design classes. Students are then expected to apply their knowledge of fabrication techniques in designing for manufacturability and better integrating design and manufacturing in undergraduate projects. Once students have completed MECH355, they are well equipped to manufacture many of their own components in their capstone design projects. Experience has shown that these activities help develop student awareness of some of the common stumbling blocks in fabricating a design. This comprehension helps improve the quality and feasibility of their design plan, rendering students more thoughtful with related decisions and more capable to assess the impact of dimensions and tolerances, and form choices on manufacturability.

Course module development

With only a single course dedicated to manufacturing and a finite amount of course material that can be covered, it is crucial to continually re-evaluate and evolve course topics and educational modules. Most recently, the focus has been placed on the consideration of emerging materials and technologies. For instance, the nondestructive test and evaluation module was created and incorporated in autumn 2005. The latest module currently under development is an introduction to manufacturing processes that support nanotechnology. Nanofabrication is the subdiscipline that deals with the development of general fabrication methodologies for the preparation of nano objects [12]. Nanofabrication methods fall into two major classes, including top-down and bottom-up. The pedagogical goal of the module is to help students understand the basic approaches of these methods in manufacturing at the nanoscale. The introduction to top-down methods builds upon silicon fabrication techniques and presents the basic principles of lithographic patterning processes and evaporation techniques. In contrast, the bottom-up, or self-assembly, approaches to nanofabrication use chemical or physical forces operating at the nanoscale to assemble basic units into larger structures. As such, the introduction is based more upon synthesis concepts from chemistry. The goal is student awareness of nanoscale concepts in manufacturing in preparation for upper level electives and industry.

Elective courses and research projects

With MECH355 being taught earlier in the curriculum, there is more time available for the incorporation of manufacturing-related elective courses. Several new courses have been developed, and existing courses improved, to offer more extensive and advanced coverage of manufacturing topics and related reinforcement and repetition. Such courses can be taken by seniors to fulfil Mechanical Engineering requirements. New elective courses developed and offered with significant manufacturing components are listed in Table 4.

The Learning Factory equipment has been valuable in the development and improvement of upper-level manufacturing courses and related

Table 4. Current elective courses with manufacturing components

Coarse	Manufacturing topics
MECH460: Engineering Optimization	Production management; Inventory control; Process optimization;
MECH462: Computer Integrated Manufacturing	Geometric modeling; Tolerancing; GD&T; Metrology, Quality and Lean Mfg; Numerical Control; Process capability and Statistical process control;
MECH466: Fracture Mechanics	Relationship between fabrication method and material failure
MECH470: Engineering Composite Materials	Fabrication techniques for composite materials.

research projects. Each course presented in Table 4, for instance, benefits from the available facility. For example, the new EDM machine is useful for the study of the microstructures of hard, brittle metals. The EDM equipment offers important new capabilities to Fracture Mechanics (MECH466), allowing for a lab experiment that analyses surface integrity in comparing residual stress formation in EDM versus conventional cutting. Also, EDM-initiated surface cracks reduce the time and cost of generating specimens to study crack propagation and fracture. This integration reinforces solid mechanics and manufacturing concepts through hands-on experimentation, and provides additional links between manufacturing and related courses.

The LF equipment has additionally provided valuable resources to faculty involved in manufacturing research. Research is critical in providing long-range capabilities of the manufacturing industry and is a vital ingredient in any manufacturing education programme. With the availability of the improved LF equipment, new research projects have been initiated involving undergraduate and masters-level graduate students. For instance, the authors are currently involved in an NSF-funded project based on the nondestructive evaluation of weld quality and the modelling of the flash butt welding process [13]. The available ultrasonic C-scan equipment has allowed for the detection of weld discontinuities and defects, vital to the project's success.

K–12 outreach projects

It is important to reach out to K–12 students and introduce them to engineering concepts so that they might consider future careers that apply mathematics and science. Often this is achieved through engineering outreach programmes offered by universities [14]. While many of these programmes include exciting technological opportunities, the vast majority of them are extracurricular in nature. As such, they are not a part of the regular curriculum and often reach only a fraction of the student population. With the help of NSF, the authors have developed a partnership with the local middle school that has resulted in enhanced technology education for the entire sixth through eighth grade population in the school district. In this way, it is believed that this effort will have a higher probability of success in attracting greater numbers of capable students to engineering, particularly females and minorities.

The most significant result of this collaboration to date has been the development and implementation of a computer-aided manufacturing (CAM) module in which each eighth grader designs and manufactures a model CO_2-powered car using the appropriate CAM software and a computer-numerically controlled milling machine [15]. The authors are encouraged by the success of this partnership and continue to consider new and exciting ways to assist with the K–12 technology education available to all students in the local school district.

ASSESSMENT

The overarching goal of each activity described in this paper is improved manufacturing education. Although there are no statistics yet to quantify the improvement or success of the enhanced manufacturing curriculum, favourable responses from the students indicate significant progress in the correct direction. Student perception surveys completed at the end of the MECH355 semester designate an average score between 4.64 and 4.81 (out of a possible high score of 5.0) in defining the value of each of the hands-on processing activities defined in Table 2. In response to questions regarding the ability to successfully apply knowledge and equipment-usage experience towards future problem solving and fabrication projects, students provided average scores between 4.31 and 4.93. In addition to these quantitative responses, student comments reflected positive and enjoyable learning experiences. Some examples include:

> 'Using the industrial-size CNC machines was a great way to learn about the importance of calculated speeds and feeds.'
>
> 'My favourite was the RP project. I would like to use the machine again to try some complex geometries.'
>
> 'I learned the hard way that plastics shrink inward during solidification and cooling.'

In addition to student feedback, data have been collected regarding the number of instances and the quantity of hours that students have used the equipment in the LF facility for laboratory activities, class projects, and/or research projects. These quantities show significant increases over the last two years, indicating improved hands-on learning opportunities for students. The outcomes also show more collaboration between faculty in mechanical engineering regarding manufacturing topics and courses, increasing numbers of manufacturing-related elective courses and education modules and increasing numbers of manufacturing research projects and related publications.

SUMMARY AND CONCLUSIONS

There is a need for curricular innovation and integration to improve the manufacturing and materials processing education offered within small, traditional mechanical engineering departments. Such departments often have only one or two faculty members with expertise in manufacturing, and usually do not have the benefit of an industrial or manufacturing engineering department within the college. It is difficult for this type of department, typically with a structured undergraduate curriculum that is highly dependent on its faculty base, to stretch its course capacity to include a comprehensive range of manufacturing principles and related applications. Consequently, innovative new practices must be executed in order to provide the students with improved manufacturing education. This paper describes an adaptation of the Learning Factory (LF) model within a small mechanical engineering department, as implemented in an effort to improve the quality of the manufacturing education offered to undergraduate students and to better address the needs of the changing manufacturing industry.

The original LF model offers a practice-based engineering curriculum that balances analytical and theoretical knowledge with manufacturing, design and business realities [9]. It is based on the premise that students learn more if they are able to do engineering while they are studying it. The success of the hands-on LF approach is highlighted by the fact that it continues to be adapted and implemented in the engineering curricula of a number of universities beyond the three pioneers [16–19]. In each case, the adapted model is an altered version of the original that maintains the overarching goal of increased hands-on learning opportunities.

The model discussed in this paper represents an LF adaptation that has been scaled down and refocused in an effort to strategically expand and improve the manufacturing education within a small department with limitations on space, curricular flexibility, and the number of faculty with manufacturing expertise. Unlike the original models that were implemented with facilities ranging from 3500 ft^2 to 6500 ft^2 of dedicated 'factory' space, this adaptation includes approximately 1000 ft^2 of dedicated space within the college machine shop. This shared space is continuously monitored by experienced technical support personnel and houses the CNC mills and lathes, the injection moulding machine and the EDM die sinker. It resides in the same room as the manual mills, lathes, drills, etc. that are also available to the students (Fig. 2). The LF adaptation additionally includes metrology equipment and nondestructive evaluation instruments that reside within mechanical engineering lab space. Although used within the described courses, this equipment is not in an openly accessible facility and therefore is less effective in regards to the ultimate goal of the LF.

The fabrication equipment that has been successfully installed in the supervised college-wide machine shop avoids the restrictions of departmental laboratory facilities and is highly utilized by students and faculty. Unfortunately, the LF prototyping, inspection and nondestructive evaluation equipment confined within departmental space is less accessible to students, and therefore not as useful on an on-demand basis. Shortcomings in regards to acquiring appropriate physical space for hands-on learning activities represent the most significant problems and obstacles experienced to date. In a culture where laboratory space is dedicated to departments and partitioned on a course basis, there is an evident degree of inefficiency. Lab spaces often sit idle other than during the time used by a single course. In addition, equipment is often duplicated within the college in order to reside in similar labs in different departments. The authors highly recommend the practice of shared, interdepartmental facilities for hands-on learning in materials processing. They are currently working with faculty in several other departments to discuss strategies to make better use of the available square footage in addressing related issues and the needs of multidisciplinary subjects. The most promising collaboration at this time is the development of a nanofabrication laboratory to enhance undergraduate engineering education through interdisciplinary courses and projects in manufacturing, design and the characterization of materials and devices with nanoscale features. This project involves faculty from several engineering departments, including chemical, biomedical, electrical and mechanical [20].

Another important aspect of the LF model is the related curricular development and enhancements. The original LF models included the creation of at least four new courses and multiple interdisciplinary design projects created to take full advantage of the new facilities. These courses were offered to students as an integral part of new minor degrees or special certificates of manufacturing and/or product realization components of existing degrees. The described LF adaptation, in contrast, is restricted by the small size of the department and the limited number of courses and faculty members available for manufacturing-related education. As a result, new course development has been limited to senior/graduate level electives (Table 4). Rather than new undergraduate courses, the curricular improvements have been focused on the creation of manufacturing modules that have been infused into existing courses. Each course module takes advantage of the LF facilities and has the most direct impact on the dedicated junior-level manufacturing course (MECH355).To maximize their educational impact, a significant effort has been placed on the timing and linking of the modules to provide simultaneous concept coverage within other departmental core courses. This task has required the cooperation and coordination of several faculty members in the department, as well as the restructuring of laboratory activities within each affected course (Table 3).

The authors believe that this approach of linking educational modules across courses taken during the same semester is largely successful. Students are presented with materials processing examples and improved hands-on learning opportunities within various core courses during the same semester. This serves the purpose of presenting manufacturing as an integral subject within mechanical engineering, and concretely relating it to the fundamental concepts learned within other core courses. This approach has helped eliminate past perceptions that Manufacturing Processes is a standalone course of special topics. The major shortcoming of the practice of linking course modules is the requirement of faculty interest, willingness and enthusiasm. Faculty members must believe in the educational benefits of their efforts and the importance of the objective. For instance, although several of the topics covered in a Solid Mechanics course can be successfully linked to concepts presented in a Manufacturing Processes course, the instructors must be willing to spend the extra time needed to coordinate the efforts and must be interested and able to properly cover the concepts. The success of the LF adaptation described in this paper would not have been possible three or four years ago, but has now benefited from the hire of several new and enthusiastic faculty members who believe in the importance of the described efforts.

The third integral component of the original LF model is that of industry partnerships and collaboration. The original models each incorporated significant industry contributions, including funds, time, equipment and senior design ideas to enhance the manufacturing education. Although future plans for the LF adaptation include the development of stronger ties with local companies, the current implementation has not yet taken full advantage of the benefits of a strong linkage to industry. At the present time, only about 20% of senior projects are coordinated with industry partners. External linkages do exist, however, with local K–12 schools. The LF has provided an efficient infrastructure for actively assisting middle and high school teachers with efforts to incorporate engineering concepts into their curricula. These activities have allowed a service learning component to be incorporated within appropriate undergraduate courses and projects. The most successful effort to date has been the previously mentioned CAD/CAM projects that are ongoing with the local middle school. Undergraduates are able to assist eighth graders with the use of CAM software and the CNC machining of their designed CO_2 model cars [15]. This partnership has proved beneficial to K–12 participants and the involved undergraduates.

The shortcoming of service and outreach projects is the fact that they do not enjoy the same perceived benefits to undergraduate education as industry collaboration in regards to funds and equipment donations. In addition, it is less common for these efforts to be rewarded within faculty tenure and review systems. As a result, K–12 outreach projects are only successful if supported by enthusiastic faculty members and if they are not discouraged by college administrators. For these reasons, long-lasting and successful outreach activities are not always feasible. However, if executed properly, they are invaluable to the growth and general health of the engineering profession.

Generally speaking, although obvious strides have been made towards improved manufacturing education with this LF adaptation, quantitative assessment of the benefits has been difficult. It is clear that further developments are required. Rising environmental concerns, for instance, are causing companies to recruit employees who understand the full impact of their engineering decisions on the environment and society in order to remain competitive in the global economy. This has led to the need to more formally incorporate educational modules on green manufacturing, and design for sustainability [21]. Interdepartmental collaboration appears to be the most promising approach with which to deal with such multidisciplinary topics. More organized cooperation across departments is needed to better address these subjects and to continue to enhance the manufacturing education programme. As previously mentioned, a significant step towards this improvement would be the reorganization of college laboratory space, moving towards subject-related usage rather than departmental labs.

Traditional interdisciplinary boundaries are not easily broken. However, steady progress is evident as a result of hiring new faculty members possessing research expertise in multidisciplinary subjects such as advanced materials and nanofabrication. Future coordination of related efforts with the departments of chemical, electrical and civil engineering will greatly enhance the quality of the manufacturing education within the college. Similarly, coordination with Operations Research courses and projects within the management department will allow research and educational opportunities in topics such as manufacturing competitiveness, global issues in manufacturing, production planning and strategy and the control of manufacturing operations.

It is expected that the success of the LF adaptation and the continued hiring of new faculty will help lead to further change. Additionally, the pressures of industry will continue to serve as motivators for further improvements and the desire to develop additional methods by which to infuse manufacturing education into the engineering curricula. It appears that globalization's dependence on the integration of technology, engineering, and business principles will continue to press departments to educate innovative engineers who are able to think across disciplines, integrate related concepts, and solve complex technical problems [22]. The LF method provides an efficient infrastructure for a curriculum poised for these challenges through the enhancements of practical experiences and hands-on learning opportunities.

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