

A hands-on approach to manufacturing education

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ABSTRACT: In this article, the authors describe an integrated hands-on approach to manufacturing education based on an adaptation of the Learning Factory (LF) model. Using coordinated projects in various courses, students generate drawings, produce process plans for and make components, and then assemble the components into a finished product. By using coordinated projects in the selected courses, students gain a good understanding of and hands-on experience with the full range of issues involved in product design, manufacturing planning, fabrication, assembly and testing of a functional product. Because it is based on modifying existing courses, rather than developing new ones, this approach can easily be adapted to other universities or programmes.

INTRODUCTION

The high cost of setting up a manufacturing facility means that universities usually have to make difficult choices about the resources they dedicate to courses in manufacturing. Consequently, many university courses in manufacturing processes or related subjects are skewed towards theoretical concepts and offer limited hands-on experience for students (if any). Frequently, students' exposure to actual processes is limited to observing demonstrations by the instructor or watching videotapes, but with students not getting their hands on the equipment. There is also the possibility of utilising simulations, but these do not offer sufficient realism [1]. Another method to overcome these constraints is to arrange for cooperative experiences that allow students to work in a manufacturing facility as part of their degree programme [2][3]. This requires extra commitment from students, since it normally entails at least one semester away from school.

THE LEARNING FACTORY MODEL

The Learning Factory concept (LF) was developed jointly by Pennsylvania State University (PSU), the University of Washington (UW) and the University of Puerto Rico-Mayaguez (UPR-M) in collaboration with Sandia National Laboratories. These were the lead institutions in the Manufacturing Engineering Education Partnership (MEEP), funded by the Technology Reinvestment Program and the US National Science Foundation. The Learning Factory concept was developed as both a new kind of curriculum and an integrated manufacturing facility. The intent of the LF concept is to create an integrated practice-based engineering curriculum that balances analytical and theoretical knowledge with physical facilities for product realisation in an industrial-like setting. It integrates a practice-based curriculum with physical facilities for product realisation [4]. Students carry out product design, prototyping and actual fabrication in an integrated laboratory.

The specific objectives of the project were to develop the following:

- A practice-based engineering curriculum that balances analytical and theoretical knowledge with manufacturing, design, business realities and professional skills;
- Learning Factories at each partner institution, integrally coupled to the curriculum, for hands-on experience in design, manufacturing and product realisation;
- Strong collaboration with industry;
- Outreach to other academic institutions, government and industry.

The concept was implemented at each of the three originating universities as a 600 m² facility at the UW, a 325 m² facility at the PSU and a 370 m² facility at the UPR-M. The LF offers students in traditional engineering disciplines an alternative path to a degree that directly prepares them for careers in manufacturing, design and product realisation. Its approach to manufacturing engineering education provides a balance between engineering science and engineering practice, with opportunities for application and hands-on experience. Students who choose this programme begin working in the LF in the first year as a direct component of their coursework and this expands in scope as they progress through their academic career. Students work in interdisciplinary teams and collaborate on industry-sponsored projects, experiencing the process of product realisation from conceptual design through to prototyping, marketing, production, quality improvement and ultimate disposal. This approach develops in students the skills of teamwork, communication, project management and problem solving [5][6].

Four new courses were developed and shared across the LF partnership namely: *Product Dissection*, *Concurrent Engineering*, *Technology-Based Entrepreneurship*, *Process Quality Engineering*, as well as interdisciplinary design projects.

The new courses were built around the following core of existing courses: *Graphics*, *Design* and *Manufacturing Processes*, which were modified in order to take advantage of the new facilities made possible by the Learning Factory. The courses were arranged into a 15-credit Certificate in Manufacturing at the UPR-M, a 24-credit Product Realization Minor at the PSU, and a 22 to 26-credit Product Realization Option at the UW [6]. The implementations also involve partnerships with local industries at each institution, with industry contributing funds, time, equipment and ideas for student projects.

A LEARNING FACTORY ADAPTATION

The LF model has been quite successful and implemented in the engineering curricula of a number of universities beyond the three pioneers [7]. In the present article, the authors describe an adaptation of the original LF model for implementation in a traditional laboratory setting, rather than a factory-like environment.

In order to accomplish the goals of the adaptation, a major project coordinated across several courses was introduced. This project serves as the unifying theme that makes the adaptation work. The specific project used is the making of a model engine that students could test at the end of the semester. Using a major project of this nature offers many advantages to students. Not only are they exposed to the important manufacturing processes themselves, but they also get to assemble the engine they make and watch it in operation. Having a functional product at the end of the semester is inherently motivating to students and affords them a sense of accomplishment and satisfaction at the end of the term. With partial funding from the US National Science Foundation, new high-quality equipment was acquired to enhance the laboratory capabilities. This made it possible to provide more realistic hands-on experiences for students [8]. The equipment acquired is detailed in Table 1.

Table 1: New laboratory equipment.

Item Description	Cost (US\$)
Geared head bench lathes with live centre, arbour and drill chuck for lathe (4)	\$16,000
Variable Speed vertical milling machines with arbour and drill chuck for mill (4)	\$26,000
2-axis digital readouts for mills (4)	\$5,000
CNC lathe with tooling and fixture set (1)	\$28,000
CNC mill with programmable Z-axis (1)	\$26,000

The actual adaptation of the LF was implemented through the modification of the four selected courses shown in Table 2. Using existing courses made it easier to integrate the results into the curriculum. Between them, these courses address a broad range of issues involved in product design, planning, fabrication, assembly and testing. This adaptation differs from the original LF model in the following ways:

- With regard to design, the target students focus more on computer-aided drafting rather than conceptual design or functional analysis. This is suitable for an engineering technology programme as opposed to the engineering programmes in which the LF model originated;
- Activities in all the courses are centred around a model engine. This retains the realism of having a functional product while using less expensive yet realistic hands-on

manufacturing equipment. Although a change in focus, this is appropriate for the targeted student body and significantly reduces the implementation cost.

Table 2: The target courses.

Course	Description
ET 2140 Computer Graphics	Solution of drafting problems and development of graphic presentations using CAD techniques
MIT 3510 Manufacturing Processes	Study of manufacturing processes like machining, welding and forming, the fabrication of materials using conventional machines, and calibration and set-up
MIT 3600 Process Engineering	Manufacturing analysis. Selection of machining parameters, tooling, and equipment. Process planning.
MIT 4700 Computer Aided Design and Manufacturing	Fundamentals of computer-aided manufacturing, CNC, 2D and 3D applications programming

This adaptation was undertaken in an engineering technology programme. Because such programmes are already practice-oriented, all new activities were integrated into existing courses and no new course or programme development was needed. It is expected that this will make the results of this work readily acceptable and transferable to other institutions desiring to employ a hands-on approach to manufacturing education.

The implementation of the concepts outlined above started with students in the Computer Graphics course ET2140 generating detailed drawings for a chosen model engine. This included developing a complete parts list, generating drawings of individual engine components and generating the assembly drawings for the engine. This was carried out in a standalone CAD laboratory. Figure 1 shows the assembly drawing of the *Pip-Squeak* model engine. The drawings generated in the graphics course were then passed downstream to succeeding courses for use as needed.

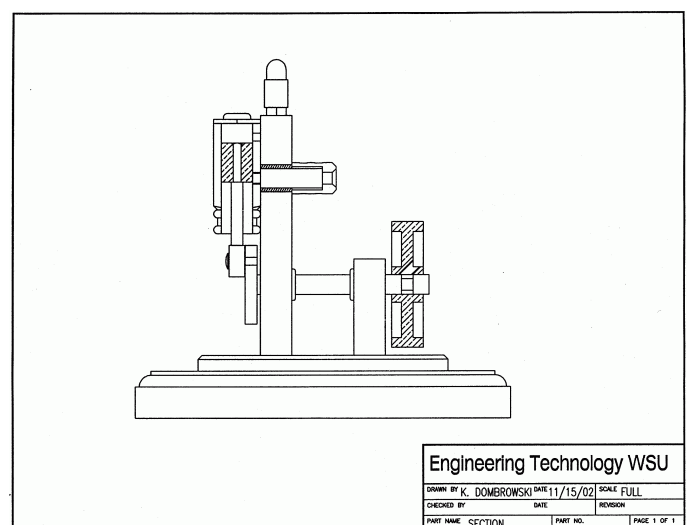


Figure 1: Assembly drawing of the model engine.

Each of the targeted courses incorporates hands-on experiences in the form of either laboratories or projects. The critical part of this adaptation of the LF model is the careful coordination of those hands-on experiences in multiple courses around the

unifying theme of the making of a model engine. As indicated above, students start in the Computer Graphics course (ET2140) by generating drawings of the various components of the model engine. These drawings are then utilised in subsequent courses for course-specific activities. For example, these drawings form the blueprints used in the Manufacturing Processes course (MIT3510), as well as the Process Engineering course (MIT3600). Similarly, the process plans generated in the Process Engineering course are used in the Computer Aided Design and Manufacturing course (MIT4700). Table 3 summarises the new activities in the various courses affected.

Table 3: New course activities.

Course	Revised Activities
ET2140 Computer Graphics	Generate fully dimensioned CAD drawings of select engine components and assembly drawings of complete model engine, including a bill of materials.
MIT3510 Manufacturing Processes	Make the engine components using conventional machine tools. Instructor gives informal guidance on process planning issues. Assemble and test the engine. Write a detailed report describing the manufacturing and assembly process.
MIT3600 Process Engineering	Generate formal process plans for fabricating the engine components using NC machines, including the determination of all machining parameters. Also generate the assembly plan.
MIT4700 Computer Aided Design & Manufacturing	Based on MIT 3600 process plans, develop NC programs to make engine components. Verify and troubleshoot NC programs. Produce engine components on NC machines. Assemble and test engine. Write detailed report describing the manufacture and assembly processes.

It is generally not feasible for any university to develop laboratory experiences encompassing *all* of the different processes covered in a typical manufacturing processes course. A choice has to be made as to the specific processes that are to be supported in the laboratory. In this case, there is a manufacturing laboratory that supports traditional machining processes, such as turning, milling, grinding and welding; this is used as the centrepiece for the adaptation.

Because making the model engine is a challenging project for students who are new to manufacturing, the semester starts off with two relatively simple components that help students get acquainted with the working of the lathe and the mill, respectively. These last about two weeks each. Once these are carried out, students are ready to start making the engine itself. They make the engine components then assemble and test the engine. A finished model engine is shown in Figure 2.

Written Communication Skills

In addition to providing hands-on manufacturing experience, the laboratories are also used to develop students' written communication skills. In the USA, this is one of the requirements for accreditation by the Accreditation Board for Engineering and Technology (ABET) [9]. Thus, students are required to write detailed reports for each project they undertake. Report guidelines for are provided. These call for the inclusion of a complete bill of materials, identification of processed parts, a description of how the parts are made,

clearly distinguishing them from off-the-shelf items like screws, and a description of the engine assembly process and testing procedure. In grading the laboratory work, both the written report and the quality of products made are considered.

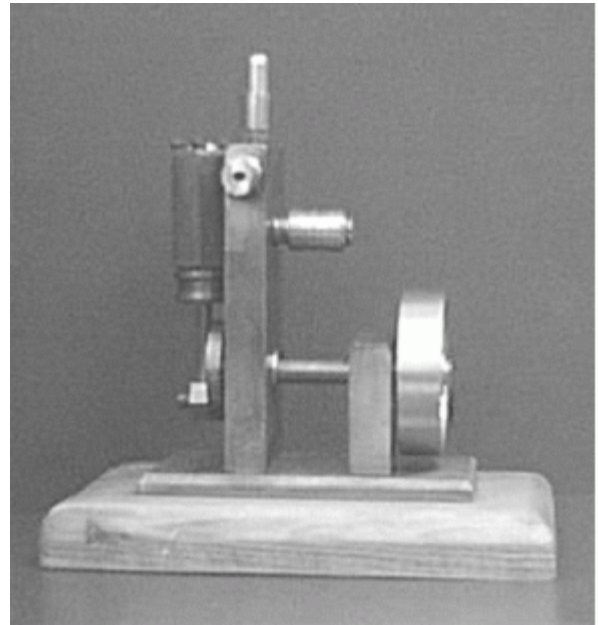


Figure 2: The finished model engine.

DISCUSSION

Prior to the implementation of this new approach, students used to complain about the quality of the machines in the laboratories. Not only was it hard to make the parts to the specified level of quality, they also felt that they did not gain an experience that prepared them well for industry. Assessments were carried out at the end of the semester to gauge student reaction to the changes that had been implemented. The assessments entailed a series of questions soliciting student feedback on a number of issues related to the adaptation. The survey instrument asked students to rate their level of satisfaction with various aspects of the course. The response options were *very happy*, *happy*, *neutral*, *unhappy* and *very unhappy*. These were then converted these into a numerical scale ranging from 5 (*very happy*) to 1 (*very unhappy*). The summary results are shown in Figure 3.

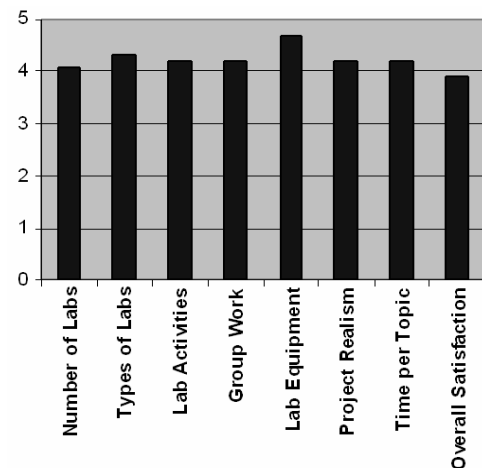


Figure 3: Student ratings of MIT 3510.

As Figure 3 indicates, the overall level of student satisfaction is quite high with a score of 4 (out of 5) or higher in every

category. The results indicate that students were happy with the types and number of laboratory projects, the opportunity to work in groups and the realism made possible by this approach. The highest level of satisfaction (at a value of 4.7) was with the laboratory equipment itself. These were very significant results for this adaptation given that its main goal was to bring realistic manufacturing experiences into the laboratory setting. The results indicate that this primary goal of the work was achieved successfully.

Ideally, students should work their way through the various course experiences in concurrent or consecutive semesters. However, this continuity may be difficult to achieve if students are not following a highly structured programme. In that case, student course selections may not necessarily mesh with the course offering sequence. In order to get around this difficulty, it was resolved to have the results from a course flow into the post-requisite course – even if some students did not. In this manner, students can utilise the results whenever they take the course. Using the same engine model every term allows students to have the same learning experiences regardless of when they take the course.

The experience gained from this work has been very positive and students have also reacted very favourably to the new approach. In particular, seeing their model engines in operation is a thrill to the students involved. It is important to point out that, from the instructor's perspective, only the nature of the laboratory content of the courses is affected by this adaptation. The lecture content does not have to be changed. This ensures that the scientific integrity of each course is preserved.

Some important issues were identified during the course of this work. Using different engine models each semester would provide variety in the work. However, this would also make it more difficult to ensure proper continuity of material for the students – especially if they have some flexibility in how they select their courses. This is because the timing that students use in taking the courses may not always match with the sequence in which the respective engines are scheduled in the various courses. Thus, a student who worked on one engine in the ET 2140 class could end up taking the MIT 3510 course during a semester when a different engine was being used. That would defeat a major purpose of this adaptation! Therefore, it is recommended that one model engine is selected and used as the basis for all the projects in all the various courses. This ensures that students work on the same type of engine regardless of when they take any of the courses. This is the approach that was adopted as part of this adaptation.

Another issue encountered was that the Computer Aided Manufacturing (MIT 4700) course did not integrate as well into this scheme as had been hoped. The reason was that there is a steep learning curve for students to understand the fundamentals of NC programming. This did not leave enough time in the semester for students to generate their own NC programs for all the engine components. One way around this would be to generate the NC programs directly from the CAD system in the ET 2140 course and then transfer those to the CNC machines. However, in practice, this was not always successful. In particular, the machine features used in the CNC machines' graphic engine could not always be recognised from

the imported CAD file. Students did not yet have the required level of NC programming expertise to make the necessary changes in the automatically generated NC programs. This points to the need for more work to be carried out in the area of integrating CAD systems and CNC controllers.

CONCLUSION

The approach described in this article uses challenging team-based laboratory projects coordinated across selected courses to help students gain hands-on experience in the design, manufacturing planning, fabrication, assembly and testing of functional products. The projects start with simple components and progress to the manufacture and assembly of fully operational model engines. These projects foster students' teamwork and communication skills that are highly sought by industry. The initial student reaction was very positive with the evaluations showing a high degree of student satisfaction with virtually every aspect of the course work.

ACKNOWLEDGEMENT

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