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Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

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ABSTRACT

Industry has consistently identified lack of experience in manufacturing processes as one of the key competency gaps among new engineering graduates. This paper discusses a laboratory-based course that provides realistic hands-on manufacturing experiences to students. The course uses team-based projects that help students gain hands-on experience with selected manufacturing processes. The projects start with simple components that can be made on a single machine such as a lathe or a mill, and progress to the manufacture and assembly of a fully functional mechanism. This approach introduces students to the issues involved in putting together a non-trivial assembly. Multiple evaluation tools including focus groups, surveys, and actual observations, were used to assess the effectiveness of the approach used. The results indicate that this is indeed an effective way of addressing industry concerns.

Keywords: competency gap, experiential learning, learning factory

INTRODUCTION

Well established educational research has shown that students' approach to learning is characterized by different learning styles while instructors have their own corresponding teaching styles [1-2]. Students whose learning styles are compatible with the instructor's teaching style tend to retain information longer, apply it more effectively, and have more positive post-course attitudes toward the subject. A variety of models for how people take in and process information and how they interact with others have been developed, four of the most well known models being: Myers-Briggs Type Indicator (MBTI), Kolb's Learning Style Model (KLSM), Herrman Brain Dominance Instrument (HBDI), and Felder-Silverman Learning Style Model (FSLSM).

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

<i>sensing</i> (concrete, practical, oriented toward facts and procedures)	vs.	<i>intuitive</i> (conceptual, innovative, theory and meaning oriented);
<i>visual</i> (favor visual presentations – pictures, diagrams, flow charts)	vs.	<i>verbal</i> (favor written or spoken explanations);
<i>inductive</i> (prefer presentations that proceed from the specific to the general)	vs.	<i>deductive</i> (prefer presentations that go from the general to the specific);
<i>active</i> (learn by trying things out, working with others)	vs.	<i>reflective</i> (learn by thinking things through, working alone);
<i>global</i> (holistic, systems thinkers, learn in large leaps).	vs.	<i>sequential</i> (linear, orderly, learn in small incremental steps)

Table 1: The FLSM Learning Styles Inventory.

The FLSM model, which specifically focus on learning and teaching styles, is especially well suited to characterizing engineering education and the work described here [2]. The FLSM model divides learning and teaching styles into five categories as shown in Table 1. Engineering instructors as academics tend to have intuitive, verbal, deductive, reflective, and sequential teaching styles while engineering students tend to have the opposite learning styles. Therefore, it takes deliberate extra effort on the part of the instructor to develop educational materials that effectively address the needs of most engineering students. The traditional lecture-based teaching styles favored by engineering academics tend to produce graduates with limited real world hands-on experience in areas favored by industry. The work described in this paper presents a new instructional approach that intentionally builds on the inherent tendencies of engineering and technology students towards sensual, visual, and active learning styles; to provide them with select competencies and hands-on skills that are in demonstrably high demand in industry.

Because traditional engineering instruction favors intuitive, verbal, deductive, reflective, and sequential learners, a gap has developed between industry expectations and the actual competencies of engineering and technology graduates. The Society of Manufacturing Engineers (SME) has identified and evaluated the competency gaps of new graduates, based on dozens of surveys and interviews with leaders from all manufacturing industries. Repeated periodically since 1997, these surveys have documented convincingly this divergence between industry and academia. Table 2 shows the key engineering competency gaps of new manufacturing graduates that have been identified by SME in the course of its investigations [3] (Note: higher ranking indicates greater need). In the current economic environment, companies are focusing more on recruiting new graduates who can make a quick contribution to corporate goals. As previously shown in Table 2, industry expects engineering graduates to have competency in a wide range of skills related to product realization. The work described in this paper focuses on

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

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1. Business knowledge/skills
 2. Supply chain management
 3. Project management
 4. International perspective
 5. Materials
 6. Manufacturing process control
 7. Written & oral communication
 8. Product/process design
 9. Quality
 10. Specific manufacturing processes
 11. Manufacturing systems
 12. Problem solving
 13. Teamwork/working effectively with others
 14. Personal Attributes
 15. Engineering fundamentals
-

Table 2: Manufacturing Competency Gaps of Engineering Graduates.

providing practical, hands-on learn-by-doing experiences that enable students to bridge those competency gaps.

CLOSING THE MANUFACTURING COMPETENCY GAPS

Various efforts have been undertaken to address the problem of new engineering and technology graduates lacking key industry skills. The Society of Manufacturing Engineers (SME) launched its Manufacturing Education Plan (MEP) in 1997 to help close these competency gaps. Since the institution of the MEP, SME has funded more than \$15 million worth of diverse projects across the US to expand and improve manufacturing, engineering, science, and technology education so as to help close these gaps. The National Science Foundation (NSF) and other funding agencies have also been involved in efforts to address these concerns. The Learning Factory (LF) concept was a major outcome of such funding efforts. The objective of the LF model was to create an integrated practice-based engineering curriculum that balances analytical and theoretical knowledge with physical facilities for product realization in an industrial-like setting. The LF integrates a practice-based curriculum with physical facilities for product realization and offers traditional engineering students an alternative path to a degree that directly prepares them for careers in manufacturing, design and product realization [4-5].

The original LF concept was developed jointly by Pennsylvania State University (PSU), University of Washington (UW), and University of Puerto Rico-Mayaguez (UPR-M) in collaboration with Sandia National Laboratories. The specific objectives were to develop:

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

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

The LF concept was implemented at each of the three originating universities as a 600 m² facility at UW, a 325 m² facility at PSU, and a 370 m² facility at UPR-M. Four new courses were developed and shared across the partnership namely: Product Dissection, Concurrent Engineering, Technology Based Entrepreneurship, Process Quality Engineering; as well as Interdisciplinary Design Projects. The new courses were built around a core of existing courses namely: Graphics, Design, and Manufacturing Processes; which were modified to take advantage of the new facilities made possible by the Learning Factory. The implementations also involve partnerships with local industries at each institution, with industry contributing significant resources including funds, staff time, equipment, internship opportunities, and ideas for senior design projects. The LF model was quite successful and it has been implemented in the engineering curricula of a number of universities beyond the three pioneers, including University of Missouri-Columbia, and Marquette University [6]. In 2006, the developers of the LF model were awarded the National Academy of Engineering's Gordon Prize for innovation in engineering education. For more details about the LF implementation at each pioneer institution, visit www.lf.psu.edu for PSU, www.me.washington.edu/resources/ilf for UW, and www.ece.uprm.edu/lfw/overview.html for UPR-M. The LF model is not easily transferable however, due to the high cost of implementing a full-blown Learning Factory, and the challenge of assembling a network of local industries willing to contribute funds, time and equipment.

The work described in this paper is based on a simplifying adaptation of the original LF concept. With NSF funding, Wayne State University undertook a project to integrate the goals and themes of the original LF model into a modified series of hands-on experiences more suited for easy implementation in a laboratory setting. The adaptation involved the coordination of realistic hands-on experiences in multiple targeted courses around the unifying theme of designing and making a model engine. Specifically with this approach, students generate drawings of the engine components then use the drawings in developing process plans and actually fabricating the components. Finally, the components are assembled into a working model engine. Each of the activities is part of an appropriate course in the curriculum and the activities are coordinated between courses [7]. Table 3 shows the courses involved in this adaptation and the related hands-on activities within each course. Follow the links embedded in the course names to see the detailed course syllabi. Between them, these courses address aspects of six of the competency gaps previously identified in

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

Course	Description	Hands-on Activities
ET 2140 Computer Graphics (3 credits)	Solution of drafting problems and development of graphic presentations using CAD	Generate fully dimensioned CAD drawings of select engine components and assembly drawings of complete model engine, including bill of materials.
MIT 3510 Manufacturing Processes (3 credits)	Study of selected manufacturing processes; Fabrication of materials using conventional machines; Calibration and setup	Make the engine components using conventional machine tools. Instructor gives informal guidance on process planning issues. Assemble and test engine. Write detailed report describing the manufacturing and assembly process.
MIT 3600 Process Engineering (3 credits)	Manufacturing analysis. Selection of machining parameters, tooling, and equipment. Process planning.	Generate formal process plans for fabricating the engine components using NC machines, including determination of all machining parameters. Also generate the assembly plan.
MIT 4700 Computer Aided Design and Manufacturing (3 credits)	Fundamentals of computer-aided manufacturing. CNC, 2-d and 3-d applications programming	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.

Table 3: Target Courses for Coordinated Hands-On Activities.

Table 2, namely: Materials, Product/Process Design, Specific Manufacturing Processes, Manufacturing Systems, Teamwork, and Written & Oral communication. The advantage is that these are addressed in the context of an actual functional product that students actually make in the laboratory. This gives students specific skills that go a long way in closing the manufacturing-related competency gaps identified by industry. A [video showing a student making one of the engine components is available here](#).

This experiential hands-on approach using a common product in multiple courses, gives students a good understanding of the range of issues involved in design, planning, fabrication, assembly and testing of a functional product. Using an integrated project of this nature exposes students to all the processes involved. Having a functional product at the end of the semester is inherently motivating to the students and gives them a sense of accomplishment and satisfaction. This approach is particularly effective for engineering and technology students who tend to be sensual, visual, active, global learners. Figure 1 shows a “Pip-Squeak” model engine made by students as a part of their coursework. A [video showing an operational model engine made by the students is available here](#).

A further adaptation of this approach was undertaken to suit the needs of students in a different department who did not have room in their curriculum for the multiple courses required in the first adaptation. Thus, with additional funding from SME and after evaluation and redesign of the original

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

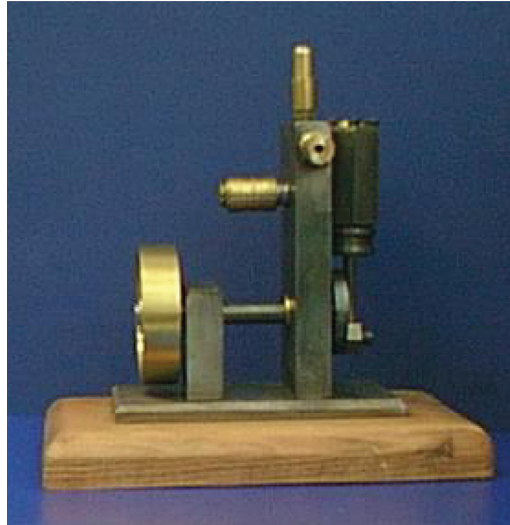


Figure 1: A Finished Model Engine.

adaptation, more simplified laboratory experiences were developed to provide more extensive but still relevant hands-on manufacturing experiences for students preparing for production management careers [8-9]. The approach taken for the new adaptation was to concentrate on giving the students hands-on experience of manufacturing processes themselves. With this new adaptation, the students do not generate design drawings or process plans of the product but instead follow directions from the instructor. Specifically, the students fabricate the components of the model engine, assemble the components, and test the final product for functionality. These different levels of implementation of the LF adaptation demonstrate the flexibility with which this approach can be used in providing engineering and technology students the important hands-on experiences they need to have in order to close the industry perceived competency gap in specific manufacturing process, process design, and teamwork.

OUTCOMES ASSESSMENT: FOCUS GROUP INTERVIEWS

The Manufacturing Processes course (MIT 3510) is the course in which students first get to use the machines to fabricate the engine components and assemble them into a functional engine. This course was used as the centerpiece of our development and evaluation efforts as it offered the greatest opportunity to achieve the goal of reducing the manufacturing process competency gap. Project evaluation was carried out over the course of two successive semesters. To help with the evaluation, an external evaluator was engaged to conduct focus group interviews with students.

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

Interviews provide a mechanism for capturing information that may be difficult to observe or that may not show up in a traditional survey instrument. Focus groups are a special type of interview that takes place within a group context rather than one person at a time. Interpersonal interactions in a focus group often lead to more detailed responses than would be possible otherwise [10]. The qualitative data obtained in the focus group setting is particularly important for our purposes because we were dealing with relatively small class sizes. In each case, the interviews were conducted close to the end of the semester after students had ample opportunity to complete significant portions of the hands-on course activities and thus could comment on whether course intent was being met. Using an external evaluator ensured anonymity for the participants.

The interviewer met with the students without the instructor or technician being present and assured the students of the confidentiality of all their responses. During the interviews, students were asked to respond to a set of questions and to indicate whether there was consensus on the response or if there was a split, to provide an indication of the range of responses. The same set of questions was used for each evaluation session. For the purposes of the interview, each class was divided into self-identified subgroups pursuing different majors. Subgroup responses were shared with the larger group and then collected. All the responses gathered were anonymous. Responses for each question are detailed below.

In evaluating the results, it is important to keep in mind that responses were gathered without comment by the interviewer. The responses are the students' perceptions and they provide an important perspective, but may not necessarily reflect a full understanding of the project constraints or goals pertinent to the class environment. The interviewer did not offer any correction or explanation of points that students brought up as the purpose was only to gather student perspective.

Question 1: *To what degree has this lab course led you to a better understanding of what it means to make a part? Do you feel that there was enough time allowed in the lab and that the manufacturing experience was effective?*

All the students agreed that the hands-on laboratory experience was very helpful for learning how to use the machines. There was a lack of agreement among the students however about the time allowed for work to be completed in the course. Some responded that the time was sufficient; others were concerned that each member of the group only had a chance to touch the lathe one time; some felt that more time was needed to make this an effective experience. Overall, the students felt that they gained comfort with basic machining operations, and gained the skills and attitudes necessary to work as a member of a manufacturing team, but they would like more time with the machines. Suggestions included:

- Simpler projects that would take less time
- An assistant for the lab technician

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

- Smaller class size
- Exposure to processes other than machining

Question 2: *To what degree has this course helped you to understand what happens at the manufacturing level, both as regards processes and part design?*

Students in all groups agreed that the laboratory course provided a feel for what happens at the manufacturing level. However, there was disagreement about the degree to which this was true. Some students felt this was true to a low degree but others felt this was true to a high degree. Some students felt that the course provided a lot of understanding in manufacturing process as well as part design and that there is more to this than what they expected. They learned more than they thought they would about material, speed, sizes, and angles and the importance of being exact. These students found it very helpful to go through the process. Overall, the students felt that they learned a lot about the basic essentials of manufacturing processes. They felt very comfortable with the machines that they worked on and that they would be able to explain to others how they work. They would like to concentrate more on CNC and on higher level technologies. They did not feel that the machines in the course were the kind that they will be seeing/using in industry.

Suggestions included making the project less “static.” Many students would like to do more than follow a design.

Question 3: *To what degree has this class helped you to better understand the language that is used on the shop floor? Do you feel better prepared, as a result of this class, to interact with others involved in the technical processes covered here?*

Most students agreed they feel much more comfortable with the language of the shop floor. Learning the names and terms has been helpful as has their degree of exposure to the decimal system. They agree that this is important to know. Students stated that, “we feel much better prepared to talk with and work with others on material related to class.” They learned new terms, sizes, names, and machines and said that they definitely benefited from interacting with each other and with the lab technician.

Question 4: *How helpful has the lab manual been in your learning and in your ability to follow lab practices?*

All students agreed the lab manual served as a good reference, especially for writing the laboratory reports and finding the names of parts. They felt it was easy to use and well laid-out. The descriptions were clear and helpful. They liked the organization of the manual and that it followed the organization of the class. The students also agreed, however, that they did not use the manual in class as it was easier to ask questions of the lab technician or each other. If no one was available to answer questions, the manual served as a useful tool, but they much preferred to ask a

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

question than to use the manual. They agreed that it will be a good reference to have in the future. Suggestions include:

- Add a cross-referenced glossary so that names can be looked up and pages provided for further information. It is too difficult to find information when looking for a specific part or concept.
- Improve the binding to make the manual more useful

Question 5: *Please evaluate the pace followed in this course: has this lab course moved too quickly, too slowly, or has it been just right?*

All students agreed that the pace of the lab class is too fast. The students did not feel that there was time for two projects plus a final project. They suggested having open lab time available. They also felt that the pacing was uneven, with the first part of the semester moving too slowly and the last part of the semester moving much too quickly.

Question 6: *Have the assignments and activities in this class facilitated your learning and understanding?*

All students agreed that the assignments and activities facilitated learning. They were very enthusiastic about the hands-on aspect of the course and that this exposed them to many things that helped them to understand manufacturing. The only concern was the amount of time allowed for the activities. All agreed that learning would be improved if more time were allowed for the hands-on portion of the class.

Some students commented that the laboratory reports require too much detail and were too much to expect. They did not understand the purpose of the reports and would like to see these shortened to summary documents. Overall, though, students agreed they are more comfortable with machining and the assignments reinforced their learning.

Question 7: *If you could change this course, what are the top 3 things that you would change to increase your learning? If this course were to be changed, what would you say should not be changed at all because to change it would weaken your learning?*

This is a standard question asked of student groups to make sure that nothing important is missed. The top answer of all students in what not to change was the presence and necessity of the laboratory technician. All agreed that without the technician, this class would not be successful or even possible. They believe that he needs an assistant to handle all the questions and issues that come up during a session. They also all agreed that the hands-on experience is the most valuable aspect of the class. Suggestions include:

- Smaller class size
- More set up time
- More laboratory time
- More modern tools/machines

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

- More exposure to each machine and to other processes as the scope of this class as it is limited
- Students would like for each person in a group to get the same amount of time on the machines
- Do *not* change lab technician

OUTCOMES ASSESSMENT: STUDENT SURVEYS

In addition to the focus group interviews, additional evaluation was carried out in the form of end-of-semester student surveys in which students were asked to rate if they agreed they had achieved the specified course outcomes. The results of the surveys are shown in Figures 2 and 3 below. For Semester I, there were 11 course outcomes (listed in the middle of the figure) and students indicated their response by selecting from five options: Strongly Agree (SA), Agree (A) No Opinion (NO), Disagree (DA) or Strongly Disagree (SD). On the right hand side of the figure, results for SA and A are aggregated under YES and the results for DA or SD are aggregated under NOT; giving a quick indication of whether the learning outcomes had been met or not. A threshold score of 75% was set to indicate an acceptable level of performance.

The results indicate that the students met the desired level of performance in all the course outcomes except outcomes 4 and 5. The results for outcomes 7 through 11 relating to hands-on

SA	A	NO	DA	SD	MIT 3510 Course Outcomes	YES	NOT
4	4	0	0	0	1. Define design and manufacturing, and describe the relationship between them.	100%	0%
5	2	1	0	0	2. Specify fit and tolerance of standardized and/or interchangeable mating parts.	88%	0%
5	2	1	0	0	3. Use preferred numbers in selection of sizes	88%	0%
3	2	2	1	0	4. Describe internal makeup of metals, and impact of this on how they can be processed.	63%	13%
3	2	1	1	1	5. Describe how at least two common engineering materials are extracted from their ores	63%	25%
4	3	1	0	0	6. Describe at least four different casting processes, and common faults found in castings	88%	0%
5	3	0	0	0	7. Given a part design, select appropriate machining processes and tools to make the part	100%	0%
6	2	0	0	0	8. Describe general safety procedures that need to be followed in a machine shop	100%	0%
6	2	0	0	0	9. Identify and operate conventional lathe, drilling, and milling machines	100%	0%
5	3	0	0	0	10. Determine the important operating parameters for each of these machines	100%	0%
6	2	0	0	0	11. Use gages such as calipers and micrometers to inspect parts	100%	0%

Figure 2: MIT 3510 Outcomes Assessment—Semester I

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

experiences (and the main focus of this work) indicated complete student satisfaction with their course experiences. There was concern about outcomes 4 and 5 that fell below the threshold and especially for outcome 5 with 25% negative rating. We looked at how students performed on the homework assignments involving these topics as an alternative way to gauge how serious of a problem this was in the course. These topics are addressed on Homework 3. The average performance on that homework during this semester was 84%, which indicates a very good level of understanding. This can be compared to averages of 77% and 72% respectively on homework assignments 1 and 2, which cover outcomes 1-3. Given this level of performance, it was decided not to make precipitous changes in the course at this stage and instead, to wait for the next semester’s evaluation results to decide if this was a real problem or just an anomaly.

Nevertheless, several changes were made in the evaluation instrument for the following semester in response to the results. It was felt that the wording for outcome 4 was not as clear as it could have been. The outcome statement was modified to improve its clarity. Also, two new outcomes were added to measure student accomplishments in teamwork and written communication, since the course used both extensively but they had not been included in the original assessment instrument. The revised outcomes and the results of the outcome survey for Semester II are shown in Figure 3. For the latter evaluation, students met the desired level of performance in *all* the course outcomes. The issues identified in the Semester I assessment did not reappear. This indicates student satisfaction with the current state of the course but the course will continue to be closely monitored to ensure

SA	A	NO	DA	SD	MIT 3510 Course Outcomes	YES	NOT
2	2	0	0	0	1. Define design and manufacturing, and describe the relationship between them.	100%	0%
3	1	0	0	0	2. Specify fit and tolerance of standardized and/or interchangeable mating parts.	100%	0%
4	0	0	0	0	3. Use preferred numbers in selection of sizes	100%	0%
1	3	0	0	0	4. Describe internal structure of metals, and impact of this on the properties of metals and how they can be processed.	100%	0%
2	1	1	0	0	5. Describe how at least two common engineering materials are extracted from their ores	75%	0%
3	1	0	0	0	6. Describe at least four different casting processes, and common faults found in castings	100%	0%
2	2	0	0	0	7. Given a part design, select appropriate machining processes and tools to make the part	100%	0%
3	1	0	0	0	8. Describe general safety procedures that need to be followed in a machine shop	100%	0%
3	1	0	0	0	9. Identify and operate conventional lathe, drilling, and milling machines	100%	0%
1	3	0	0	0	10. Determine the important operating parameters for each of these machines	100%	0%
4	0	0	0	0	11. Use gages such as calipers and micrometers to inspect parts	100%	0%
3	0	1	0	0	12. Communicate effectively using written and graphical modes.	75%	0%
3	1	0	0	0	13. Work successfully as a member of a team	100%	0%

Figure 3: MIT 3510 Outcomes Assessment—Semester II

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

outcomes are met. Meanwhile, the additional outcome items indicated high student accomplishment in teamwork and written communication.

DISCUSSION

The two modes of evaluation undertaken gave plenty of useful information to help assess the effectiveness of this new approach. Responses to the first three questions in the focus group interviews, (Q1, Q2, Q3), show strong agreement among the students that they learned how to use the machines, gained comfort with machining operations, learned the basics of machining processes, and learned the language used on the shop floor. All these strongly suggest that the goals of the project were met by this approach. This conclusion is supported by the results of the end-of-semester surveys, which by the second semester, showed that all course outcomes were being met at the 75% level or higher. In particular, learning outcomes 6–10, which deal with the hands-on aspects of the course, show 88% level of satisfaction or higher for *both* semesters. The results of the focus group interviews together with those from the surveys are very strong evidence for the effectiveness of this approach in bridging the industry-identified competency gap in manufacturing processes.

One of the strongest themes identified in the focus group interviews was a desire by the students to have more time allowed for the projects (Q1, Q5, Q7). The course instructor remains convinced however that while challenging, the work involved is not excessive. This is buttressed by the fact that while they did complain, the students were able to complete all the projects and produce a functional mechanism. The instructor believes that this is one of those cases where some 'push' is appropriate to get the students to achieve at a higher level of performance than they would consider themselves capable of. Interestingly, the students also expressed a desire to experience other types of processes (Q1), or other types of machines (Q2) which would require additional effort! There appears to be a conflict of goals here that had to be resolved. The solution we came up with is described in greater detail below.

In light of the above assessment results, as well as input from an advisory board of industrial experts representing local manufacturing enterprises, our initial LF adaptation was modified further. The new modifications were made to allow students more time to carry out the required machining tasks, and to also expose them to additional manufacturing processes. With this in mind, the product made by the students was changed from a model engine to the model machine vise shown in Figure 4. The vise entails less overall machining work but still requires the same types of operations on the machines. While the revised product can be completed in less time, it still provides enough in-depth experience to attain all the learning outcomes of the course. Because the simplified product

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

can be completed in less time, the balance of the time can be used to give students more hands-on experience of additional manufacturing processes.

To give students exposure to other types of manufacturing processes, a project involving sheet metal bending and welding to make a storage box has been added to the course. In this case, as with the machine vise project, students make the components and assemble and weld them into the final functional product. This gives students multiple exposures to an even wider range of processes for manufacturing a fully functional product. Figure 5 shows the storage box at different stages in the manufacturing process. The expressed desire of students for experience on CNC machines in particular (Q2, Q7) could not be accommodated in this course. As shown in Table 3, there is another course, MIT 4700, which addresses Computer Aided Manufacturing. Students will get an opportunity to be exposed to CNC machines in that course.

Whereas the work described here focused on providing students with hands-on experiences of manufacturing processes, the underlying concept can be applied in other fields of engineering. By

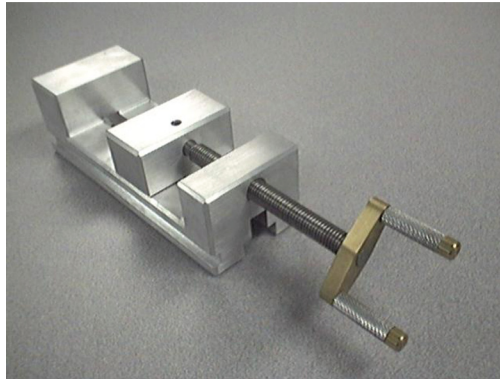


Figure 4: Finished Machine Vise.

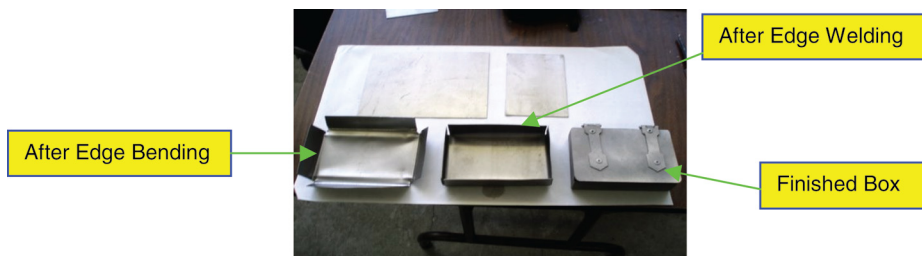


Figure 5: Key Steps in Box Manufacturing.

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

designing challenging and realistic projects that require the use of practical skills, instructors can help students develop the skills that prepare them to function effectively in industry upon graduation. Not only does this approach circumvent the high cost of a fully functional Learning Factory, it also provides a middle ground between internship/co-op experiences that require students to take off time from school, and the traditional classroom based instruction. However, implementing the approach successfully requires creative thinking by instructors as they adapt their teaching styles to meet the learning needs of their students.

In terms of future work, a more direct assessment of student learning styles and rigorous evaluation of learning exercises in relation to student learning styles could inform further curriculum design and evaluation efforts. While the dimensions of learning styles such as the visual vs. verbal distinction offer considerable face validity and intuitive appeal, it would be preferable to evaluate instructional materials with regard to these dimensions with validated, reliable instruments. Such a rating could then be used to examine relationships between the learning style affected by the material and the learning styles reported by students.

Future development efforts could also benefit from a more direct assessment of student learning at the course outcome level. Combined with student self-reports, direct assessment could provide a more complete picture of the degree to which this course is closing the competency gaps identified by industry experts. Program-level outcomes assessment, where actual employers are interviewed with regard to the performance of students who complete this course can simultaneously validate the learning outcomes of the course, the students' performance, and the ongoing relevance of the applicable skills of graduates to determine if the competency gaps this work was aimed at reducing have indeed been closed.

CONCLUSION

The approach described in this paper uses challenging team-based laboratory projects to help students gain hands-on manufacturing experience based on the fabrication, assembly and testing of a functional product. The projects are designed to close key manufacturing competency gaps for engineering students and foster teamwork and communication skills that are highly sought by industry. The reaction of our students has been enthusiastic and multiple course evaluations have shown that the educational objectives of the course are being met. Students have proposed several improvements in the course, some of which have already been implemented, and others that are under active consideration for future offerings of the course. The students showed a high degree of satisfaction with most aspects of the course work. We anticipate similar success can be realized at other institutions that adopt a similar approach to engineering education.

Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

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Closing the Competency Gap in Manufacturing Processes As It Applies To New Engineering Graduates

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