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Abstract:

At Marquette University, hybrid project-based learning has been implemented in an undergraduate mechanical engineering course on materials processing and forming using a team-based approach. The goals of the project are to 1) introduce more active and student-centered activities to improve student engagement and mastery of core concepts, 2) increase students' confidence in their ability to apply what they learned in the course to

solving real-world problems, 3) enable students to gain experience using engineering software as part of the learning process and in applications contexts. While use of process modeling software in materials processing and manufacturing courses is not entirely new, the project has students actively developing a model around a realistic process, rather than passive users running “canned” models and reviewing the output. This paper presents details of the project and discusses preliminary results regarding its impact on student learning and confidence related to application of the course concepts. Recommendations for improving and expanding this in-class project are presented, along with a description of the assessment methods used to measure the impact on students.

SECTION I. Introduction

Recently there has been an increased level of interest in understanding how students learn in order to improve learning effectiveness and comprehension [1]–[2][3][4][5]. As a model is instructive for this purpose, it is useful to consider how engineering skills are acquired and to use this as a basis to implement practice-based learning activities and improve student skills. The process of formal skills acquisition, as opposed to skill gained through trial and error, can be modeled using the five stages of skill acquisition proposed by Dreyfus and Dreyfus [6]–[7][8]. This model (referred to in this paper as the Dreyfus model), which was originally based on a study of United States Air Force pilots, has also been applied to study skills development in the medical profession [9] and is also relevant to engineering. It should be noted that the Dreyfus model describes particular skill development traits rather than individual talent levels.

According to the model, a person acquiring a skill proceeds sequentially through several stages: a) novice, b) advanced beginner, c) competent, d) proficient, and e) expert stages. In applying this model to undergraduate engineering education, several implications can be discerned. A key idea is that student experiences in a traditional lecture-based engineering course are necessary to produce skills commensurate with the novice level. However, the expectation of most stakeholders is that by the time a student graduates, the engineering curriculum will enable students to develop skills that correspond to the level of an advanced beginner.

The issue of competency gaps raised by industry and the level of interest in project-based and problem-based learning provide some evidence that many graduates are not developing the expected skills [10], [11]. Recognizing this, an increasing number of instructors are modifying courses in an effort to integrate more applied, hands-on content and improve student engagement. Many of these changes involve the inclusion of active, project-based, collaborative, and other forms of student-centered learning, which have been shown to improve student learning [11]–[12][13]. Active learning is an instructional method that engages students in the learning process. In active learning students conduct meaningful learning activities connected to what they are doing. While this definition could include traditional activities such as homework, in the education literature active learning most commonly refers to activities that are introduced in the classroom. The core elements of active learning are activities that engage students [14], [15]. Active learning is often contrasted to the traditional lecture format where students passively receive information from an instructor.

Given the hierarchical nature of engineering education, the Dreyfus model suggests that rather than eliminating the novice steps, it is necessary to introduce experiences that allow for more open-ended learning and independence on the part of the students. In order to facilitate the transition from novice to advanced beginner stages, additional experiences such as hybrid project-based learning (PBL, a form of active learning) could be included in a way that allow for situational aspects to be introduced and tailored to the desired level within a project context. An additional consideration is that computer-based technology has transformed professional engineering practice, but this is not the case in education where it tends to be used more as a means to automate the existing educational process rather than as an integral tool for learning and student inquiry [16]. Although computer and virtual based technologies are routinely used in industry for engineering and manufacturing work, many students are not conversant or being trained in virtual and digital technologies which are increasingly pervasive in professional practice. However, properly structured, such technologies can be effectively utilized for student learning and skills development in hybrid PBL.

SECTION II. Project Rationale

One of the key goals of an upper level engineering course is to enable students to achieve skill traits that are more similar to those of advanced beginners than novices. When the nature of skills development is considered, it can be argued that the exclusive use of traditional lectures and textbook problem solving activities is likely to improve knowledge but keep students at a novice skills level. We hypothesize that 1) the level of student competence in a course can be increased to that of an advanced beginner in part through the use of virtual/simulation tools, and 2) this effect is measurable.

Although engineering skills encompass a diverse range of activities, ABET learning outcomes c) an ability to design a system, component, or process to meet desired needs within realistic constraints, e) an ability to identify, formulate, and solve engineering problems, and k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice [17] were most consistent with the intended project activities and scope. Thus, ABET outcomes c), e), and k) served as the framework for structuring the project activities and assessing its impact.

SECTION III. Background

Processing & Forming of Materials (MEEN 4440) is a fourth year elective offered at Marquette University in the Department of Mechanical Engineering and was used as a pilot course for the project. The emphasis in MEEN 4440 is on solidification and thermo-mechanical working and includes coverage of microstructural development in castings, melting processes, process-property relationships, and mechanics of metal forming processes. A first course in manufacturing processes is a pre-requisite for MEEN 4440 and develops skill traits that are consistent with a novice. In the past, MEEN 4440 has been offered as a lecture course. Although the course met student expectations, it was concluded that while they were able to perform analytical tasks, they struggled with using the concepts in an engineering context and demonstrated a low level of engagement/ownership in the learning process. PBL implementation in upper division courses necessitates that due to the greater technical depth that some degree of structured learning needs to be retained. Because of this, hybrid forms of PBL are well suited to engineering and were chosen for the project.

Given that a key requirement in a PBL environment is for students to produce a product/outcome, it follows that available resources at an institution will limit the type and scope of project work that students will be able to perform. In much the same way that simulation software provides practicing engineers with a powerful virtual tool that can be used for design and verification; the flexibility that such programs (particularly discrete simulation and manufacturing process modeling software) offers also make them highly effective as a learning tool in an academic environment. This is particularly true in manufacturing processes where computer-based visualization can convey concepts more effectively than text, equations, and two-dimensional images and promote student retention [18]. In comparison to a lecture-based course, PBL represents a natural environment where students can not only develop application skills using computer-based technology as part of the engineering process, but they can also use this technology as an *integral tool for self-directed learning* [19].

While materials processing provides a wide range of potential project topics, a project developed around forging process design was considered to be the most appropriate choice as it could be structured to be consistent with student skill levels and the course syllabus. Rather than using a contrived design problem, PBL philosophy indicates that an industry-based problem would provide more student motivation and connection between course content and real world problem solving. A Wisconsin company was contacted and agreed to furnish a forged gear blank geometry. Although impractical for students to actually demonstrate their process, finite element method (FEM) based process simulation enables them to build a realistic virtual model that includes the relevant materials processing physics. The ability to receive timely feedback is also an important element in PBL. By using an axisymmetric part geometry, simulation times are relatively short (on the order of 10 minutes using a laptop computer) and students are able to receive feedback regarding their design decisions and assess how well they meet the stated requirements.

To prevent skills development from being diluted and creating activities that were potentially confusing to students, it was decided that a unified, integrated approach using a single project was necessary. The project was structured so that students were provided with a set of specifications and a part print at the beginning of the semester. Students were then paired and tasked to develop a three-step prototype process that met multiple constraints. As students typically have little experience and familiarity with FEM and forging design principles, it was necessary to dedicate 2–3 class periods to cover basic concepts in these areas. Pre-project testing showed that in order to ensure that the project focused on engineering skills development rather than software usage, it was crucial to employ software that was user friendly and easy to navigate. A number of engineering software vendors have recognized that similar needs exist in industry and now offer easy to use interfaces and wizards to reduce the learning curve for beginning users. For the current project, the commercial code DEFORM (Scientific Forming Technologies Corporation, www.deform.com) was used.

In addition to using process modeling software, students also employed solid modeling to develop the necessary geometry files for the initial work piece and tool geometry. Using the post processor, students must verify that their process produces a sound forging and maintains conditions that are within workability limits for the alloy. Each team must also select an appropriate tool material and verify that stresses are within acceptable levels (i.e., below the 0.2% yield strength) based on a yield criterion. A further requirement was to demonstrate that the force profile was consistent with the kinetic envelope for a crank-slider press mechanism. To ensure that students and the instructor could monitor progress, a set of milestones and a timeline were developed with interim design documents being submitted by each team. This also provided an opportunity for the instructor to provide corrective feedback as needed and monitor the extent that key concepts were being explored by each group.

SECTION IV. Results and Discussion

The project was implemented in Fall Semester 2012 with an enrollment of 18 senior-level mechanical engineering students of which 51% had co-op experience and less than 20% had FEM experience in prior coursework or employment. Due to the low level of experience students had with FEM modeling at the start of the project, several activities were assigned as part of the interim reports that required students to investigate selected modeling concepts (e.g., mesh design) and consider the effect they had on the model performance. While there was initially some concern about students' ability to develop proficiency using the FEM software, 74% of the students were able to use the FEM software after initial training sessions with the remainder requiring minor technical advice. Most of the problems encountered were attributable to students being unsure how to approach an open-ended design problem. This was addressed through as-needed meetings between the instructor and groups to allow the instructor to provide suitable suggestions. It became apparent however, based on the interim documents submitted, that there was a need for students to improve their drawing and dimensioning abilities.

Although it is not a trivial task to assess engineering skills levels, the Dreyfus model does provide a description of attributes at each skill level that can be used to guide development of metrics. Applied to engineering practice, an advanced beginner is capable of situational discrimination and working with both context-free features and situational aspects to formulate a plan of action. This behavior is evidenced when students become less dependent on rote rule/procedure following, can independently discern which factors are important in solving the problem (i.e., situational discrimination), and are able to arrive and execute a workable solution albeit with some effort.

To determine the impact of the project on student design capability and ability to meet multiple design constraints, student success rates were determined with respect to whether or not their final design met each of the design specifications. The percentages of student teams meeting the project design criterion are shown in Table 1. While none of the teams were completely successful, 78% of the teams were able to meet 5 out of the 6 specified criteria though the low success rate in the blocker design task was unexpected. However, after using the software it was concluded that self-directed experiences alone were not sufficient to develop design skills. After reviewing the traits noted in the Dreyfus model, this suggests that it will be necessary to include additional design maxims and examples in future project assignments.

When considering how to assess the effectiveness of project oriented learning, it is necessary to consider attitudes and skills rather than simply comparing knowledge orientation as is done in traditional subject learning [18]. Students were asked a series of questions intended to conduct a self-assessment of their ability to design a process and use FEM as a modeling tool. A total of 17 students were assessed before (pre-test) and after (post-test) the project. These were intended to measure their abilities to perform a design and use a modern software tool as part of engineering practice. Pre ($\mu1$)/post ($\mu2$) evaluations were compared via a standard test of means (t-test) as well as a non-parametric test of means (Mann-Whitney U-test).

Based on their responses to questions regarding 1) understanding and confidence in designing a manufacturing process, 2) understanding thermal phenomenon in materials, and 3) understanding and applying effective stress in an applications, students were asked "How confident are you in your ability to design and model a manufacturing process?" Responses to this question were used to form a hypothesis for testing. Pre-test questions indicated that 64% of the students had low confidence in their ability to design a manufacturing process (question 1). Based on these results the hypothesis: "A student's ability to model a manufacturing process has improved" was proposed with the alternative hypothesis: "It is unknown if a student has improved his/her ability to model a manufacturing process". Results from the t-test and U-test are given in Table 2.

Load Profile-Blocker	**Load Profile-Finisher**	**Die Fill - Blocker**	**Die Fill-Finisher**	**Die Stress-Blocker**	**Die Stress-Finisher**
89%	78%	11%	78%	89%	78%

TABLE 1. Percentages of student groups meeting each of the six project design criteria.

Test $(\mu_2 > \mu_1)$	**Calculated Probability (P-value)**	**Significance**
t-*test*	3.5×10^{-9}	Yes
Mann-Whitney U-test	2×10^{-8}	Yes

TABLE 2. Assessment of student ability to design a prototype materials processing operation.

Based on the results of both tests, it can be concluded that a statistically significant (small p-value) improvement was observed with respect to students' ability to design a prototype manufacturing process based on hot forging.

Responses to questions regarding 1) understanding how nodes function in FEM, 2) understanding of mesh design, 3) understanding of mesh density, and 4) understanding and ability to use information from the FEM model, resulted in students being asked "Do you understand Finite Element Analysis as it is applied to a manufacturing process?" This led to the hypothesis "A students' understanding of Finite Element Analysis as applied to a manufacturing process has improved," with the alternative hypothesis "It is unknown if students' understanding of Finite Element Analysis as applied to a manufacturing process has improved". Results from the t-test and U-test are given in Table 3.

Based on the results of both tests, it can be concluded that a statistically significant improvement was observed with respect to students' ability to understand the basics and use of FEM with respect to a manufacturing (forging) process.

An effort was also made to incorporate the modeling software as part of homework problems and exam questions in place of analytical calculations. This was done on a limited basis to ascertain if self-directed learning would increase understanding of the fundamental importance of effective stress and could be used to replace class discussions. One of the questions posed on a mid-term exam asked each student to define and discuss effective stress in his/her own words. Of the responses, 52% were deemed satisfactory and, while not conclusive, it is consistent with findings from other studies that PBL does not necessarily lead to an improved understanding of fundamental concepts.

Test $(\mu_2 > \mu_1)$	**P-value**	**Significance**
t-*test*	4.7×10^{-10}	Yes
Mann-Whitney U-test	1.2×10^{-8}	Yes

TABLE 3. Assessment of student ability to understand basic concepts and use of a finite element model related to manufacturing processes.

Student feedback regarding the value of the project and what was learned from it was solicited. The following is a sample of quotes from students who completed the course:

"*I actually enjoyed working a lot with this software and it truly gave me a much better understanding of the whole forging process. I kind of wish we could have had more class time to fool around with the program. Other than that I think the use of this program for the mini-project was a great idea and very beneficial*."

"*I loved the project as it involved a real part made at a local company*."

"*I learned a lot about the different things that must be considered in the die forging design process including load requirements, die stress, temperature, fill, friction, etc. I have also gained a good understanding of the use of the DEFORM program and feel confident in my ability to simulate and assess forging operations*."

"*I learned many things such as how to use DEFORM, the relationships of temperature, stress, material flow, friction, contact time, etc. in a forging process, and I learned and understand more forging terms*."

"*Working with simulations allowed me to see how I could affect the outputs of a forging process by varying input parameters. Being able to see directly how I could affect results greatly facilitated my comprehension of course material*."

"*I gained a better overall understanding of processing as well as an appreciation for all of the time that goes into doing it correctly*."

Student feedback indicated that students liked working on a real-world problem, learned about the forging process and other course material, and developed an appreciation for the many parameters involved in designing a forging process.

Due to the user friendliness of the software, minimal class time needed to be dedicated to the project from regular lecture discussions. Students were able to focus on self-directed learning using the software to study and visualize fundamental behavior while receiving more detailed feedback than would be possible in lecture, text reading, or visiting a website. While the project focused on materials processing, the experiences gained indicate that it not only provided suitable project/ design experiences that can be used in a semester project, but that comparable efforts could also be applied to other courses. For example, a similar scaled-down project is being prepared for use in the pre-requisite junior-level manufacturing processes course for basic concepts related to materials forming. This would not only help to improve vertical linkage between the courses but also enable more time for coverage of necessary design maxims and examples without significantly reducing class time needed for coverage of other syllabus topics.

SECTION V. Conclusion

Hybrid PBL learning was implemented in an undergraduate mechanical engineering course on materials processing and forming through a team-based project. The goals of this project were to 1) introduce more active and student-centered activities to improve student engagement and mastery of core concepts, 2) increase students' confidence in their ability to apply what they learned in the course to solving real-world problems, and 3) enable students to gain experience using engineering software as part of the learning process and in applications contexts.

Based on the assessment results of the project completed in the MEEN 4440 course, we conclude that the goals of the project were met and the project experience improves students' ability to 1) design a prototype manufacturing process based on hot forging, and 2) understand the basics and use of finite element analysis with respect to a manufacturing (forging) process. While some refinement is needed, student response to the design experience and software usage was very positive and the project will become part of regular course activities.

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