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Assessing the Learning Gains of Manufacturing Students in an Integrated Hands-on Curriculum

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1. Introduction

Traditional engineering instruction tends to favor intuitive, verbal, deductive, reflective, and sequential learners, even though most engineering students tend to fall in the opposite categories of sensing, visual, inductive, active and global learners[1-2]. A consequence of this is a lack of practical hands-on experience among many fresh engineering graduates, which is one of the major competency gaps in manufacturing education[3]. Educational methods and materials that address the needs of students outside of the above favored categories would improve overall student learning. Although the use of experiential learning techniques is becoming an increasingly popular way to address these concerns, the learning gains directly attributable to such techniques have not been formally quantified.

The National Science Foundation (NSF) and other funding agencies have invested extensively in projects promoting various forms of experiential learning. Noteworthy among these was an NSF grant to the Manufacturing Engineering Education Partnership, which developed an integrated practice-based engineering curriculum called the Learning Factory (LF). The LF balances analytical and theoretical knowledge with physical facilities for product realization in an industrial-like setting. It stresses hands-on engineering activities and industry collaboration, and offers students an alternative path to a degree that directly prepares them for careers in manufacturing[4-5]. A drawback of the LF model however is its high implementation cost, which limits its transferability.

2. Development of the MILL Model

Our team pioneered and implemented a cost-effective adaptation of the LF model. The modified approach entails projects coordinated across multiple courses to give students targeted hands-on competencies[6-8]. Project activities culminate in the fabrication of a functional product in a Manufacturing Processes course. The goal was to give students practical experience in the complete range of activities involved in the design and making of a product. The adaptation was refined along the way, and in the process we demonstrated that it is important to have ***flexibility*** in how it is implemented. This led to broadening of the effort, to involve five academic programs at four separate institutions. The institutions involved were: Wayne State University (lead), New Mexico State University, Prairie View A&M University, and Macomb Community College. The work focused on four related knowledge areas: (1) drafting and design, (2) manufacturing processes, (3) process engineering, and (4) CAD/CAM/CIM.

Each institution had specific program objectives and therefore the number and sequencing of courses required to cover the material varied. To make the work independent of the institutions, course-level student learning outcomes in the four knowledge areas were identified. A curriculum writing process was undertaken which narrowed these down to a common core meeting the needs of all participating institutions. Relevant courses at each participating institution that encompass the four knowledge areas and their learning objectives were identified. This provided the initial curriculum mapping matrix, which was subsequently subjected to a statistical analysis to identify the common core learning outcomes across the four institutions. Because of differences in curricular structure and content at the various schools, the initial relationship between project outcomes and course outcomes was not necessarily isomorphic. A given institutional course learning objective could contribute to more than one project knowledge area. A weighted average score was computed according to Equation (1):

$$\overline{x} = \frac{\sum_{i=1}^{n} wX_i}{\sum_{i=1}^{n} w_i}, \qquad (1)$$

where X = the raw score,
w = the weight,
and n = the total number of scores.

A weighted average rank was computed because the number of courses involved, and the outcomes identified within each course differ among the participating institutions. The weighted averages, however, were only meaningful within an institution and not informative across schools. In order to transpose the relative rankings into a common metric, the weighted averages were then converted to a *standard normal score* ($\mu = 0$, $\sigma = 1$) using Blom's algorithm[9], a proportion estimate based on $r_i \left(1 \le r_i \le w\right)$. This produced a normal curve Z score according to Equation (2), corresponding to r_i such that

$$\Phi^{-1} = \left(\frac{r_i - \frac{3}{8}}{w + \frac{1}{4}} \right), \qquad (2)$$

where $\Phi^{-1}\left(\cdot\right)$ = the Gaussian cumulative density function,
w = sum of the case weights,
and r = rank.

The relative weighted percentiles for each school were then calculated from the cumulative probability of the normal distribution for each Z score. The consortia schools naturally differed in emphases. Therefore, a mean percentile for each outcome was computed across participating schools. Following this approach, similar rankings were developed for all four knowledge areas. The common 'core outcomes' across consortia schools were defined as the set of outcomes that ranked at or above the 50^{th} percentile. The resulting common core, implemented at all four institutions, forms the ***MILL Manufacturing Competency Model*** (MILL Model for short)[8], which is shown in Table 1. Note that the CIM component did not make the cut to be part of the common core for the four institutions and was eliminated.

Between them, these core outcomes cover a broad range of issues involved in product design, planning, fabrication, assembly, and testing. They constitute a core body of knowledge that all graduating engineers and technologists in manufacturing related fields should master. Focusing on the learning outcomes makes it easier for other interested institutions to implement the resulting model because instead of force-fitting a new curriculum into their programs, they can simply map their outcomes to the MILL model outcomes. This is accomplished by using only those courses that are most relevant to their program outcomes. The adopting institution simply maps the MILL course-level learning outcomes to its institutional program outcomes. This makes the MILL Model highly transferrable.

Table 1: Curricular Framework for the MILL Model.

Manufacturing Processes		**Process Engineering**	
M1	Given a part design, select appropriate machining processes and tools to make the part	P1	Plan and analyze part design for productivity
M2	Determine the important operating parameters for each of these machines	P2	Analyze and improve manufacturing processes
M3	Describe selected manufacturing processes, including their capabilities and limitations	P3	Analyze tolerance charting in part design
M4	Identify and operate conventional lathe, drilling, and milling machines	P4	Apply logical design of a manufacturing process plan
M5	Communicate effectively using written and graphical modes	P5	Perform manufacturing process planning of a given part
M6	Work successfully as a member of a team	P6	Communicate effectively in oral and written formats
M7	Specify fit and tolerance of standardized and/or interchangeable mating parts	P7	Select the optimal manufacturing equipment
Drafting/ Design		**CAD/CAM**	
D1	Use a state-of-the-art CAD program to develop parametric solid model representations of parts and assemblies	C1	Describe and identify geometric modeling in CAD domain
D2	Visualize objects 3-dimensionally	C2	Perform computer-aided numerical control programming
D3	Create orthographic views of objects		
D4	Create 3D models using wireframe and solid modeling		
D5	Sketch objects freehand to communicate concepts		
D6	Create constraint-based modeling using a state-of-the-art CAD program		

Implementing the MILL Model entails modifying *existing courses* by incorporating appropriate hands-on activities that address targeted student learning outcomes. Implementing the model into existing courses makes it highly sustainable and readily transferable. The key innovation is to coordinate the hands-on activities in multiple target courses. Students encounter the same ‘unifying product’ from different perspectives as they progress through the curriculum. Thus, students get to address the wide range of issues involved in the design, planning, fabrication, assembly and testing of the selected product. The selected product can be unique to each institution. The unifying products used at the four institutions pioneering the MILL Model included a model engine, a machine vice, a model windmill, and a hammer. Sample products made by students are shown in Figure 1.

Figure 1: Sample 'Unifying Products' Made by Students.

The results of this work showed that curricula differing in their detailed implementations can be developed based on a common set of learning outcomes. The core learning outcomes were structured to help meet ABET student learning outcomes, satisfy industry-identified gaps in hands-on manufacturing experience, and satisfy the institutions' respective program-specific objectives. It also showed that students can acquire important hands-on competencies under the MILL Model.

3. The Proprietary Standardized MILL Assessment Instrument

The MILL Model was structured to help address the industry-identified gaps in hands-on manufacturing experience, meet ABET student learning outcomes, and satisfy the respective participating institutions' specific program objectives. Current ABET criteria show a major shift away from reporting on process "inputs" (e.g., number of credit hours, volumes in the library). The focus has instead turned to institutions demonstrating through assessment and evaluation that they are reaching their desired outcomes[10]. This need to document program level outcomes implies that curricular innovations like the MILL Model also need to demonstrate their effectiveness in meeting the stated outcomes.

There are two primary assessment methodologies used in the field of engineering education, namely: (1) descriptive (or qualitative) designs that describe the current state of a phenomenon, and (2) experimental (or quantitative) designs that examine how a phenomenon changes as a result of an intervention[11]. An emerging third methodological approach, called "mixed methods" involves the collection or analysis of both quantitative and/or qualitative data in a single study[12]. To assess attainment of student outcomes under the MILL Model, an experimental design was used to develop a proprietary parallel forms standardized test incorporating a hands-on manipulative to provide direct assessment of student learning. Normed scores were established based on results from all four participating institutions. The drafting/design, manufacturing processes, process engineering, and CAD/CAM/CIM knowledge areas formed the subscales of the test. Each subscale contains multiple competencies, which formed the test blueprint. An artifact designed to exhibit the hands-on skills expected under the MILL Model was created to accompany the test. It provides an experiential manipulative to be referenced during the test to tie in with relevant hands-on experiences. The test content was validated by academic and industry experts, and subjected to rigorous psychometric analyses by evaluation experts to ensure its reliability and validity.

Testing at the consortia schools provided data for analyzing the psychometric characteristics of the instrument. Content validity of the test was assessed by the blueprint approach to test construction. The psychometric structure of the test was pursued through an item deletion approach. Parallel forms reliability, obtained by administering two different versions of the test to the same students, was 0.86 (p = 0.006; meaning the result was statistically significant). Internal consistency reliability measuring the internal homogeneity of subject matter, as obtained via Cronbach's α, was 0.80; and obtained by the unbiased parallel model r_{PM} was 0.81. The standard error of measure was 1.82.

In a standardized test, the average item difficulty (*P)* should be close to 0.5 in order to maximize item discrimination (the ability to differentiate the performance between a student who has mastered the material and a student who has not). A *P* value close to 1 indicates an easy item and a value close 0 indicates a hard item. At 0.61, the mean *P* value for all test items was close to the desired middle point. The item discrimination statistics for the test were obtained via discrimination and point-biserial methods. The statistics were further broken down by grouping students into low and high ability levels. The top 27.5% students were placed in the high ability group, and the bottom 27.5% were placed in the low ability group. An item with discriminatory ability should be correctly obtained by students in the high ability group, but not by students in the low ability group. The data showed strong discriminatory ability for all test items. Sample results at competency level are shown in Table 2. The results indicate that this is as a high-quality standardized instrument for assessing student achievement of MILL Model outcomes.

Table 2: Sample of MILL Test's Item Difficulty and Discrimination Statistics.

Item #	Competency	Item Difficulty P	Discrimination Index D	Endorser	
				Low Ability	High Ability
1	C1	.3214	.45	.10	.55
2	D1	.7857	.30	.55	.85
8	M2	.4107	.46	.25	.70
20	P7	.5536	.65	.20	.85

4. Establishing Learning Gains Attributable to Curricular Innovations

Although there is growing use of project-based learning in engineering, less has been done to formally assess the learning gains *actually attributable* to these types of approach. Our work to date has established that (a) the MILL Model is an innovative curricular reform that provides students with hands-on skills highly sought by industry, and (b) we have developed a psychometrically reliable and valid standardized assessment instrument to measure student achievement on the competencies spanned by the MILL Model. The current project brings these two together through a formal summative evaluation of the MILL Model; to compare the learning gains achieved under the model, with the learning gains attained by comparison groups studying the same content but without participating in a MILL Model-type curriculum.

This work will ascertain the extent of learning gains actually attributable to implementation of the MILL Model (if any). This proof-of-concept, using a standardized test incorporating a physical manipulative to evaluate attainment of hands-on engineering competencies, is groundbreaking and is expected to be a significant contribution to the field. The four MILL implementing schools and three comparison schools are involved in the current project. The comparison schools were chosen due to the overlap in many demographics of potential interest such as gender, ethnicity, and other school-based criteria.

The hierarchically arranged courses in the MILL implementing schools have previously been set to facilitate the use of systematically coordinated hands-on activities culminating in the making of a unifying functional product. For example, the specific courses at Wayne State University are Computer Graphics, Manufacturing Processes, Process Engineering, and Computer Aided Design & Manufacturing. The unifying, functional product in these courses is a model engine. Other MILL implementation schools have similar courses with their own respective unifying products. For the comparison schools, students will be selected to participate from among the students enrolled in courses covering the concepts listed in the MILL Curricular Framework in Table 1. The MILL standardized assessment instrument will be administered at all participating schools. The data on student performance will be transmitted to investigators at the project coordinating site for analysis and evaluation.

This project will use psychometrically validated standardized testing to evaluate and validate attainment of target hands-on competencies. This is an innovative use of standardized testing for programmatic evaluation as opposed to standard comparison curricula. It can document attainment of specific targeted learning outcomes for various assessment purposes, including accreditation. The relative performance of the two groups on the standardized test will document the extent of learning gains attributable to the MILL intervention. By comparing performance on the test instrument between intervention groups and comparison non-intervention groups, the project will document the learning gains attributable the MILL Model intervention. In a unique assessment of the effectiveness of a curricular innovation, the results of this work will ascertain the relative magnitude of the effectiveness of the MILL Model intervention on student learning.

5. Expected Project Impact

This project will promote learning through validation of the MILL Model which promotes teaching geared to the learning styles favored by most engineering and technology students; and deployment of psychometrically validated standardized tests to assess learning. This project also helps to broaden the participation of underrepresented groups due to the diversity of the institutions involved. Table 3 shows the anticipated demographic breakdown of students in the project. Clearly, the project will inherently serve a diverse population including underrepresented groups, many of whom are first generation to college. The project team also reflects this diversity and includes minority as well as female faculty.

Table 3: Demographic Impact of Project.

School	Percent Distribution		
	% Female	% Hispanic	% Black
Oregon State University, OR	8	1	1
Henry Ford Community College, MI	12	3	28
Macomb Community College, MI	5	5	30
New Mexico State University, NM	50	50	2
Prairie View A&M, TX	29	0	88
University of Southern Mississippi, MS	18	5	22
Wayne State University, MI	20	0	25

Affirmative results regarding the superiority of learning gains for students in MILL-based curricula, along with a unique standardized assessment incorporating a realistic physical manipulative, will poise MILL Model for a national scale-up.

Finally, the MILL project has direct benefits to society. It will increase workforce preparedness for industry by reducing industry-identified competency gaps. As called for by the SME Education and Research Community, this project will demonstrate a flexible, effective, low cost curricular model to prepare a skilled workforce that meets industry needs. This will help to foster the competitiveness of US industry and thus support overall economic development.

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