Closing Competency Gaps in Manufacturing Through Student Learning Factories - One Approach

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Abstract

In the traditional model of manufacturing education, the manufacturing processes course has been offered with a lab component while other manufacturing related courses are offered as lecture only. Linkage between courses is often not implemented in the curricula. A second issue is the growing movement towards closing competency gaps that have been identified by educators and industry. This paper discusses an approach being taken at Marquette University to help close competency gaps and incorporate a higher level of horizontal integration between manufacturing courses using the Learning Factory approach. Rather than limiting usage of the manufacturing lab to one course, it instead forms an integrated environment for hands-on learning across the manufacturing curriculum using a variety of manufacturing technologies. As one means of assessing this approach, the impact of the methodology is being measured using a quantitative index (ν-function) which was developed at Marquette University for measuring the quality of soft indices.

Introduction

Over the last decade, engineering education has undergone a number of significant reforms. One of the most far-reaching has been the movement towards integrating a larger practice-based component within the undergraduate curricula. This response has been triggered in part by industry criticism that engineering students are entering the workforce with significant competency gaps, which has necessitated remedial training on the part of the employer. While much of the focus has been centered on competency gaps related to design experience, similar concerns have been identified in graduates with respect to manufacturing related skills[1]. In addition to communication skills, other manufacturing related competency gaps that have been identified by employers include application of manufacturing processes, statistics, and manufacturing systems. While specific reasons for manufacturing related skills deficiencies have not been identified, it is likely that the reduction in hands-on laboratory experiences that was effected at the same time that design content in the curricula was being reduced is one of the primary causes.

A second criticism of engineering education has been that there is little effort to integrate parts of the curriculum[2]. Students often echo this view when they complain that courses are too "theoretical" and that they fail to see how coursework relates to professional practice. In manufacturing education, this lack of integration has also contributed to competency gaps with respect to understanding the systems nature of manufacturing. While the "Tayloristic" approach of compartmentalizing manufacturing along functional lines and teaching specific functions in separate courses (Figure 1) is an effective means for developing student skills within these areas, there is typically little integration or application of concepts across courses. Consequently students often do not connect how these activities relate and fit together within a manufacturing enterprise.

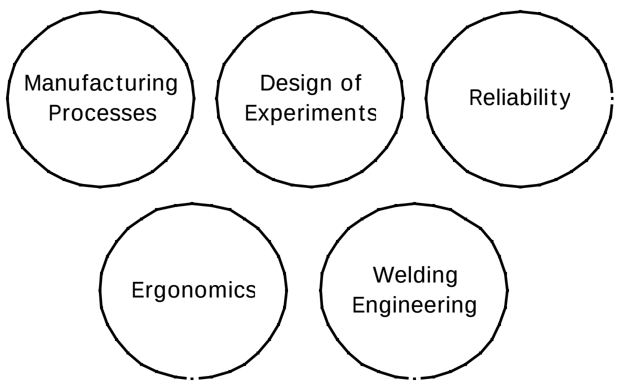

Figure 1. Traditional approach to manufacturing instruction.

The question then arises as to how manufacturing educators can implement learning activities that help to close competency gaps and establish a connection between manufacturing concepts and courses. While alternative methodologies have been developed for engineering instruction in the last decade, hands-on experiences and application remain effective means for developing student learning and professional skills. While industry has indicated that coursework should stress application of manufacturing principles over theoretical treatment[1], the danger with a purely practical approach is that students tend to be trained in technical skills which in many cases will be obsolete within a few years of graduation. One proposed solution is to incorporate practice-based projects or collaborative projects with industry[3]. However, this is not always workable in larger classes and for first courses in manufacturing. Assigning projects also does not ensure experiences that feature hardware-based problem solving or enhance understanding of manufacturing equipment, both of which are valued by employers and an important feature in developing application skills. Our approach has been to adapt the Learning Factory concept. While Learning Factories have been implemented at a number of universities and manufacturing extension sites, most academic learning factories are focused on integrating design and manufacturing rather than emphasizing integration of manufacturing principles. Learning Factories located at manufacturing extension sites, while well equipped with state-of-the-art equipment and skilled personnel, may be remotely situated and do not always enable a high level of participation and student interaction.

This paper summarizes results to date of a Learning Factory, which has been developed and implemented at Marquette University in the Mechanical & Industrial Engineering Department. The purpose behind the Marquette Learning Factory is to realize increased levels of practice-based learning experiences and achieve a greater degree of horizontal integration between existing courses in the manufacturing curricula. One characteristic of the Marquette Learning Factory is that it is manufacturing centered and emphasizes integration of manufacturing concepts in a setting that resembles an industrial facility rather than a traditional laboratory. Unlike traditional labs, the Learning Factory tailors instruction in fundamental manufacturing concepts towards their application in a factory setting. Because the Learning Factory is not course specific, a common environment can be used to develop and integrate concepts across crosses and promote opportunities for inter-disciplinary learning.

II. Student Learning Factory – Concept and Background

At Marquette University, manufacturing courses are taken by Mechanical and Industrial Engineering students as required or elective courses. While most manufacturing courses are required coursework for Industrial Engineering students, a significant percentage of Mechanical Engineering students opt to concentrate in manufacturing through elective coursework. The impetus for the Learning Factory arose in Fall 1997 when the state of the manufacturing curricula and labs was being assessed and evaluated. At that time, a traditional lab structure was in place with lab facilities being dedicated to the manufacturing processes course. Substantial reliance was placed on use of "bridge" experiments, simulation, and small-scale tabletop equipment. Practice-based activities were not a regular feature in any of the other manufacturing courses. While student analytical skills were consistently strong, the faculty felt that student ability to apply concepts and make technical inferences needed to be strengthened. Student enthusiasm and satisfaction with the manufacturing courses and labs was also found to be mixed.

As a result, it was decided to restructure the lab curricula using a Learning Factory design to include hands-on practice-based activities and integrate manufacturing principles.

Because functions such as reliability, ergonomics, and statistics are normally centered around and used to support production operations, manufacturing processes comprise the primary activity in the Learning Factory and are used as the basis for establishing linkages to other manufacturing courses (Figure 2). Rather than studying functions as discrete blocks in isolation from other manufacturing activities, the Learning Factory enables manufacturing processes to be integrated in an application based context. Students do not just collect and analyze data but can also set up a specific process and optimize it using statistical-based methods. Because activities are performed in a common environment, inter-relationships that exist in manufacturing can be highlighted and better comprehended by students. Moreover, most activities are hardware-based which not only helps to solidify student understanding of concepts through visual learning but also provide experiences that have a readily discernible connection to real world activities. A second advantage of the Learning Factory environment is that students are able to investigate how equipment and tooling impact different aspects of manufacturing such as variability and ergonomics, an activity that directly relates to industrial practice.

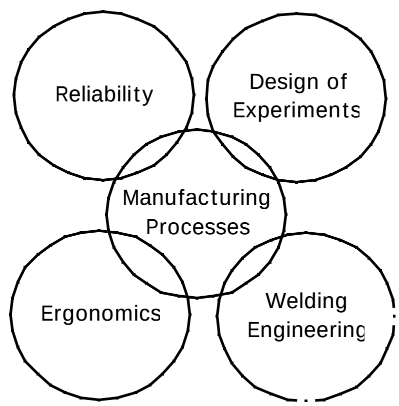

Figure 2. Manufacturing course integration using the Learning Factory environment.

The Learning Factory at Marquette University is equipped with general-purpose machine equipment, instrumentation, data acquisition equipment, and tooling that form a flexible training environment where students can engage in manufacturing experimentation or prototype manufacturing. The Student Learning Factory is organized to resemble a job shop with dedicated work areas for manufacturing and experimentation, product dissection/metrology, and a secured tool storage area. A decision was made to equip the Learning Factory with manual machines rather than CNC equipment initially. This was due in part to concerns that usage would be limited by the need for programming skills and that students would lose sight of desired engineering principles while learning skills to operate CNC equipment. Because it is not feasible to outfit the lab with equipment for individual students to work on, students work in teams with lab activities designed such that each group member has a function to perform. This has also been advantageous since students who have had prior shop or manufacturing experience are paired with inexperienced students to facilitate peer-peer learning. While student safety and ability is always a concern whenever equipment is used, our experience has been that engineering students are both capable and safety conscious. Prior to beginning any new topic, students undergo orientation and training in equipment use and must be able to demonstrate that they know how to operate any piece of equipment prior to using it in any activity. Students can also access detailed operation sheets at any time via the worldwide web to review machine operation and nomenclature.

Currently the Learning Factory is used in four junior level and one senior level course that include Manufacturing Processes 1 and 2, Design of Experiments, Ergonomics, and Welding Engineering. Plans are being made to incorporate other courses in the near future. In the manufacturing processes course, students engage in activities covering metrology, machining, joining, and forming. While the remaining courses do not have a formal lab component, the Learning Factory provides a forum to perform short-term projects and conduct other active learning activities in a manufacturing environment. One example is in the ergonomics course where the Learning Factory is used in to quantitatively assess trunk motion during a simulated machining operation. In the design of experiments course students now plan and execute different experimental designs centered around specific manufacturing processes to develop recommendations for processing rather than simply analyzing canned data. Such experiences are also advantageous in that students have can engage in more rigorous and challenging lab activities that develop technical report writing and other communication skills. Minimal time is needed to train students in equipment use in other courses since comprehensive training is provided during the first semester of the junior year in the manufacturing processes course.

The flexible nature of the Learning Factory has also permitted a more inter-disciplinary learning environment. In the past, joint learning exercises with other departments and non-manufacturing disciplines has been limited. In the senior level welding course, a series of interactive, joint class sessions between Mechanical/Industrial and Civil Engineering students has been conducted. Students enrolled in the welding course have conducted demonstrations and fabricated weldments for students enrolled in the bridge design course. In turn, students in the welding course have been able to observe tests of the weldments conducted by the Civil Engineering students and have been able to experience first-hand the effect of welding on field performance. This has been very timely in light of recent problems at the Hoan Bridge in Milwaukee. Although the Learning Factory focuses on manufacturing activities, it is flexible enough to allow the relationship of manufacturing to product and process design to be considered as part of coursework. One of the activities currently used in the manufacturing processes course is a reverse engineering assignment where students disassemble a small gas engine and analyze a designated component. After generating a CAD drawing, students are required to develop a process sheet identifying the steps and processes they think were used to manufacture the part taking tolerances and finish into account.

III. Assessment of the Learning Factory

A significant challenge associated with any new learning methodology is measuring the impact on students. Although obtaining objective feedback through questionnaires and grades is often a difficult task, such instruments still represent a meaningful basis for assessment. The assessment of the Learning Factory as it related to student learning was investigated through the use of a quality-planning tool developed at Marquette University [4,5]. This tool, termed the *v*-function, treats a student's questionnaire, regarding their course experiences, as a scientific instrument. A questionnaire is a suitable means for collecting information regarding quantities such as quality or customer satisfaction because such quantities are generally multi-dimensional. To insure that a questionnaire measures consistently, sensor reliability, based upon an internal consistency parameter known as Cronbach's alpha[6], must be monitored if a controlled evaluation is to proceed:

$$\hat{\alpha} = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k} \hat{\sigma}_i^2}{\hat{\sigma}_X^2}\right)$$

Reliability values above 80% are typically deemed excellent in terms of sensor construction[7]. To determine if a sensor actually measures what is intended, the concept of validity must be explored. In as much, a sensor to evaluate student satisfaction was specifically designed according to the specifications associated with the Learning Factory experience. Reliability and validity are monitored and can be improved through questionnaire modification.

A latent variable (a variable which is not directly measurable) θ, was defined as: θ : *student's satisfaction with discipline MEIE 143, Manufacturing Processes* to assess the outcome from all activities associated with the implementation of the Learning Factory. This is essentially a measure of student satisfaction with the Learning Factory approach in MEIE 143. Currently work is underway to extend the methodology to assess student skills. According to psychometrics, θ, is located in the latent space with *s* dimensions and is represented by the vector θ_0. Therefore, one can express θ_0 as a function of its vector components:

$$\theta_0 \equiv (\theta_1, \theta_2, \cdots, \theta_s)$$

While the latent variable, θ_0, can not be assessed directly, its components or dimensions θ_1, θ_2, … θ_s are often easy to assess through straightforward questions. These components are individual quality traits associated with the latent variable as a whole. Moreover, the variability in the latent variable must ultimately result from the variability of its dimensions.

A multiple linear regression equation can be designed such that:

$$\theta = c + b_{\theta\theta_1.\theta_2..\theta_s}\theta_1 + b_{\theta\theta_2.\theta_1..\theta_s}\theta_2 + \ldots + b_{\theta\theta_s.\theta_1...\theta_{(s-1)}}\theta_s$$

where $b_{\theta\theta_1.\theta_2..\theta_s}$'s are the regression coefficients obtained from partial correlation coefficients (the subscript means correlation between θ and θ_1, partialled out the rest of the θ components) and c is the intercept. The estimate of θ is then written in the usual form:

$$\hat{\theta} = \theta + \phi$$

where: $\hat{\theta}$ is the estimate of the value of the latent variable obtained through regression

θ is the theoretical parameter of the latent variable, and

ϕ is the noise stemming from the measurement process.

If this noise component is further denoted as:

$$\phi = -\Delta\,\varepsilon$$

the noise can be decomposed into a systematic term Δ, which arises from the imperfections of the sensor in missing some of the dimensions (not asking all the right questions) which make up θ, and a random measurement term ε. Examining the variability of these error terms:

$$\sigma_\phi^2 = \sigma_\Delta^2 + \sigma_\varepsilon^2 - 2\operatorname{cov}(\Delta, \varepsilon)$$

a common conclusion is that $\Delta \quad \varepsilon$ therefore $cov(\Delta,\varepsilon)=0$. If the variability within the sensor due to sensor construction or dimension omission can be reduced, the discrimination quality of the measured index can be markedly increased.

If an artificial latent variable, $\tilde{\theta}$, is introduced which is directly measurable without being deployed into dimensions: $\tilde{\theta} = f(\tilde{\theta}_1, \tilde{\theta}_2, \tilde{\theta}_3, \ldots, \tilde{\theta}_s)$ where $\tilde{\theta} \quad [0,1]$, a unimodal measure of the underlying trait under investigation may be explored. An estimate of such a variable would come from simply asking how an examinee feels about the quality of the learning experience in MEIE 143. Since this summary question is, in effect, made up of the same dimensions as those deployed in the multi-question sensor it is clear that $\tilde{\theta} = f(\theta)$. This equality is named the *v*-function (where *v* stands for validity) and given the symbol γ. This validity index is a measure of the sensor exactness. A value of $\gamma = 1$ would mean a perfect sensor (all dimensions present were examined). The *v*-function is modeled as a logistic ogive whose values range from 0 to 1. Further development of these quantities can be found in Pereira 1997[4].

The quality control system used to insure the integrity of content and pedagogy will be one of feedback control. This type of system consists of 5 components:

1.) *A Sensor*, in this case a questionnaire developed to survey the understanding of project goals by all participants of the project.
2.) *A Goal*, in this case the satisfaction of the implemented pedagogy of the Learning Factory in MEIE 143.
3.) *A Discriminator*, in this case the evaluation will measure the difference between the previous methods employed in this course and the performance and the goals established above. Descriptive statistical measures (means, variances) as well as inferential statistics (reliability coefficients, observed correlation, inter item correlation and covariance) will be presented as obtained.
4.) *A Decision Maker*, in this case the course instructor along with the sensor construction team will determine actions to be taken based upon the output presented by the evaluation.
5.) *A Deployer*, in this case all users of the Learning Factory must be informed of needed corrective actions.

In this feedback system, the questionnaire developed by the sensor development team is used for regular data collection. Discrimination is a natural output of the data collection and analysis process. Any non-conformance to project goals should lead to system correction and subsequently system improvement. Only if the sensors capability and quality continually improve, will the confidence intervals about the Learning Factory outputs be continually reduced. Once measures with reasonably small variability are obtained, the goal of continuous improvement can be measured.

The population of this evaluation consisted of seniors and juniors who were majoring in either Mechanical or Industrial Engineering. The first measurement consisted of 60 undergraduates and was taken in 1997, prior to the implementation of the current Learning Factory. The second measurement consisted of 40 undergraduates and was taken in 1998, again prior to the Learning Factory. These two measurements were taken during the initial development of this evaluation strategy. At this time, it was an anti-dotal conclusion among the faculty participating in this course that students were not happy with the workload, especially the laboratory experiences. 100% of all students taking the course during these two measurement processes were included. The third measurement was taken during the fall of 2000 after the first semester long implementation of the Learning Factory and consisted of 35 undergraduates. Statistical analysis of both the pilot sensor and subsequent final sensor were based on the following:

1. Sensor application: Data collection
2. Exploratory data analysis: Normality assumption, uni-modal or multi-modal distribution, and outliers

3. Descriptive statistical analysis: means and variances.
4. Inferential statistical analysis: Reliability coefficients, observed correlations, average inter-item correlations, and covariances.
5. *ν*-function statistical analysis.

The final sensor was composed of seven dimensions, each of which a series of questions (sub-dimensions) were asked to quantify, namely:

θ_1 *Goals and class design (4 sub-dimensions)*
θ_2 *Professor Personal Characteristics (4 sub-dimensions)*
θ_3 *Professor Performance (15 sub-dimensions)*
θ_4 *Teaching Assistant Performance (6 sub-dimensions)*
θ_5 *Technical Lab Experiences (8 sub-dimensions)*
θ_6 *Technical Classroom Environment (5 sub-dimensions)*
θ_7 *Non-Technical Classroom Environment (8 sub-dimensions)*

The questions each had a 4 interval scale where 1 = Poor, 2 = Fair, 3 = Good, 4 = Excellent. The following Table provides a summary of the three measurements taken.

Table 1. Summary of sensor results using the ν-function in MEIE 143 at Marquette University.

	1997		1998		2000 w/ LF	
Dimension	$\hat{\theta}_d$	$\sigma_{\hat{\theta}_d}$	$\hat{\theta}_d$	$\sigma_{\hat{\theta}_d}$	$\hat{\theta}_d$	$\sigma_{\hat{\theta}_d}$
1	2.58	.51	3.19	.42	3.17	.45
2	2.87	.70	3.60	.50	3.50	.54
3	2.66	.48	2.85	.54	3.13	.46
4	2.59	.60	3.21	.61	3.17	.53
5	2.44	.60	2.98	.51	3.39	.42
6	2.67	.45	2.80	.49	2.87	.38
7	2.74	.49	3.15	.41	3.14	.52
Artificial Latent Variable						
$\hat{\tilde{\theta}}_p$	.58		.61		.69	
$\sigma_{\hat{\tilde{\theta}}_p}$	.19		.17		.13	
Sensor Reliability						
$\hat{\alpha}$	.82		.81		.85	
Validity Index						
γ^*	.94		.91		.93	

As seen by this data, the mean value of all dimensions, except teaching assistant performance, have increased when the Learning Factory was implemented in the fall of 2000. The laboratory experience (dimension 5) went from 71.4% to 84.75% satisfaction while the variance was reduced. Student satisfaction with the learning experience has increased significantly and indicates that the Learning Factory has made a positive impact on student learners. The reliability and validity of this sensor are seen to be quite high. This means that any improvement in the sub-dimensions that make up the latent variable will ultimately improve the learners satisfaction with MEIE 143. As the Learning Factory is improved, one would expect further increases in the mean values of dimension 1, 5, and 6.

Additional evidence of the Learning Factory impact has come from student evaluations and comments. In the Design of Experiments course where the Learning Factory was used to conduct machining based experiments for the first time, students wrote comments that even though this meant extra work for them, it was well worth the effort in terms of what they were able to learn. Not only has the quality of written lab and project reports shown improvement, student enthusiasm regarding the extra work for such class activities is also noticeably higher.

IV. Summary

The Learning Factory has not only enabled practice-based learning experiences to be introduced into the curricula but has enabled students to better understand how different manufacturing functions fit together through horizontal linkage of manufacturing courses. The Learning Factory has enabled course instructors to take classes to the Learning Factory for lectures while using the equipment. Our experience has been that such discussions are more dynamic and that students are less timid in the Learning Factory where they tend to ask more questions in comparison to a traditional lecture setting. Student response to the Learning Factory to date has been very positive and in a number of cases students have made requests to use specific pieces of equipment for conducting course work and projects. Based on student feedback from the fall of 2000, 87% of the students stated that they liked the Learning Factory concept and wanted to use it in other courses in addition to the manufacturing processes course.

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