Teaching an Undergraduate Manufacturing Course using a Design-based Teaching Approach

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Abstract:

Introduction to Manufacturing Processes is one of the core courses in most mechanical engineering, manufacturing engineering, and industrial engineering programs. The current course curriculum and teaching style mainly depend on the lectures for the manufacturing processes that are aligned and synchronized with the laboratory work (project) to gain the required knowledge and skills.

According to students' feedback for this course as well as similar courses offered at other universities, the course is time intensive, involves no critical thinking, requires limited class participation, and is not well connected with real-world manufacturing problems.

The approach implemented in this work is based on using students' micro-lectures (seminars) and design-based projects to deal with different manufacturing topics from an engineering design point of view using passive/active/constructive learning approach rather than using the traditional lecture style. Each student needs to work individually or in a group to collect information about selected manufacturing processes using online and offline resources (passive learning). Each study group shares their resources with other groups before the lecture and during the lecture through a 20-30 minutes seminar. The students need to be ready to discuss and exchange their ideas about the selected topic with other classmates (active learning).

Also, a manufacturing design-based projects for a real engineering product or part, with a challenging set of questions, is assigned to each student to improve students' scientific/engineering knowledge and critical thinking beyond the classroom experience (constructive learning).

In this work, learning modules related to the casting process and the product assembly processes and tolerances analysis topics are presented.

The learning outcomes from the application of the design-based teaching approach are reflected through the students' successful completion of the project activities, in addition to gaining a lifelong learning and communication skills through micro-lectures preparing and presentations. Besides, the students learned how to use a computer-aided design (CAD) package to engage in advanced design-manufacturing analysis which is valued in industry.

Introduction and Background

Instructors are always trying to find a passionate way to teach their courses to support student's success efficiently and effectively. Also, the continuous increase in the needs for new technical and nontechnical skills in the modern work environment represents another pressure factor on the universities to update student's learning outcomes to meet the demand of the contemporary industry and business to up-to-date qualified workers. Thus, teaching style needs to be updated continuously to reflect the direct and indirect changes in the learning and work environment. In general, during the past decades, education became more focused on hands-on project-based teaching approaches, used more interactive, open-ended problems, and required more feedback about the problem-solving process which is proven to be more effective and can lead to increased student learning [1].

Several teaching approaches were implemented to improve student's leaning outcomes by integrating active/passive learning and real life projects. For example, Graham et al. [2] used the Paul-Elder framework of critical thinking to define and operationalize critical thinking for the Electrical and Computer Engineering program students. Students are taught explicitly about critical thinking followed by explicit critical thinking exercises in the introduction to engineering course to prepare students to embrace more elaborate, discipline-specific, critical thinking required of them in future courses. At sophomore, junior, and senior levels, courses were selected for critical thinking, and professional ethics emphasizes. The students were encouraged to use critical thinking skills to analyze requirements and constraints which would apply for advanced real-world problems. Significant improvement in critical thinking skills of students have been achieved through this sequence.

An integrated thinking approach is adopted by Katz [3] to bridge the educational gap between analytical and design thinking for mechanical engineering students. The suggested approach is implemented by reforming science engineering courses by stressing the physical interpretation of mathematical derivations to analyses and design simple mechanical devices; then modifying project-based design courses to emphasize the analysis part of the creative design process. A positive feedback from the students suggests that integrated thinking might be successfully applied in many areas of ME education to create continues education patterns in ME education.

A multi levels sequential design project is used by Ansaf and Jaksic [4] to increase students learning outcomes in design analysis and critical thinking. The students implemented required design modifications of a product in a systematic time-based procedure using traditional and nontraditional design tools (finite element analysis). The results show an improvement in student engagement in the course topics and in critical thinking.

Okojie [5] claims that "in a highly competitive manufacturing industry, the total cost of design and manufacturing can be reduced and hence increase the competitiveness of the products if computers can integrate the whole working procedures. Computer-aided integration has, therefore, become an inevitable trend. Many industries have achieved a great deal of success between non-integrated and integrated systems."

Egelhoff et al. [6] described "a structured problem-solving approach which uses the students' understanding of free-body-diagrams, shear and moment equations, and energy methods. With the development of note-taking handouts supplied to the students, the structured analysis is led by the instructor using Castigliano's theory of internal energy. The problem formulation is kept general until the last step. The numerical integration can be performed in software of the students' choice."; Egelhoff et al. [6] "found that using this approach accomplishes a richer, deeper understanding of design among our students and increases their confidence as indicated by our pre- and post-activity assessment."

Wendel [1] used a flipped classroom teaching approach to teach an intermediate undergraduate manufacturing class at the Massachusetts Institute of Technology. According to Wendel [1], the initial students' survey indicated that this intermediate-level manufacturing class was not related to "the real world," was not interesting, and was also time-intensive. The feedback from students showed the class to mostly promote informative learning as opposed to concept-based learning and critical thinking. Implementing the flipped-classroom approach, pre-recorded videos were used to prepare the students for a lecture. Then students in pairs participated in challenges during the class time related to the lecture topic. The results showed increases in student participation during lecture time. Also, the students noted their preference for advanced scientific content in class.

In this work we address improving the teaching approach of an introduction to manufacturing processes course for mechatronics and industrial engineering students at our university. In general, manufacturing processes is a cornerstone foundation course in many engineering programs. The traditional objective of this course is to engage students with principles and concepts of traditional and nontraditional manufacturing. The suggested teaching approach is developed to include several learning components that can help create an active/passive/constructive learning environment for the students. Student's micro-lectures are used to improve lifelong learning skills and create an interactive teaching environment with the instructor and other students. Also, a design-based project is used to strengthen constructive concept-based learning and critical thinking for the students. Assessments and survey results are used to evaluate the performance of the suggested teaching approach.

Course Description

Introduction to manufacturing processes is the first course in the manufacturing sequence. It is needed for engineers dealing with any manufacturing discipline either working on a factory floor or in a design environment. Students are exposed to introductory principles and concepts of traditional and nontraditional manufacturing. The course includes processes like casting, metal forming, machining, welding and semiconductor manufacturing. It is a four credit course offered for junior students (3 hour lecture and 2 hour Lab)

Prior to this course, the students had freshman and sophomore level courses and we expected the following prerequisites by topic:

1. Basic engineering drawing practices and tolerances
2. Basic physics concepts: velocity, acceleration, force, torque, energy, power, heat, fluid dynamics
3. Descriptive statistics, geometry, trigonometry and calculus

4. Material properties: strain, stress, strain rate
7. Graphing 3D objects and system assembly using SolidWorks©,

The number of students in this course is 24. The course it taught only in the spring semester.

Course Implementation

The course is taught by first introducing each topic, then presenting examples, in-class assignments and projects, and finally assigned homework. The class assignment sets are designed to allow students to practice and sharpen their problem solving skills. In addition, the students are allowed to work in teams to solve in-class assignments during lab time.

a. Students' Micro-lectures (MLs)

To create passion and interactive course learning environment students' micro-lectures for a selected topics were introduced and implemented during class period.

Each student (or a group of students) prepares 20-30 min presentations to show his/her/their essential findings related to the selected manufacturing process. The micro-lectures focus on the important features and applications of the selected manufacturing process. Video segments and simulations can be used to enrich students' understanding of a manufacturing process. Peer evaluation is used to evaluate micro-lectures in addition to the instructor evaluation. Participation in peer evaluation and discussions is necessary for the final assessment of the micro-lectures. It is expected that the micro-lectures demonstrate essential aspects of the manufacturing process as an added value for the information in the lecture notes. The students are urged to start working on their designated topics when the related chapter is started, as listed in the lecture notes. The micro-lectures weight 15% for the final grade. (75% for the presentation and material quality, 25% for peer evaluation). SMLs improve learning skills for the students to achieve the lifelong learning goal. In addition, this learning approach allows more time to focus on problem-based assignments and mini projects during class time. The students' micro- lecturer topics covered through this study are listed in Table 1.

Table 1 Micro-lectures topics

#	**Micro-lecture topic**
1	Selective assembly and tolerances analysis
2	Sand casting process
3	Centrifugal casting process
4	Vertical casting process
5	Investment casting process
6	Refractory casting process
7	Die casting process

b. In-class Projects and Labs

A real-life engineering product with a challenging set of questions is used as an in-class project to improve the critical thinking about different manufacturing operations beyond the classroom walls. To accommodate project analysis the simulation tools in SolidWorks are used. For the dimensions and tolerances analysis in the assembly process, the students work on a design tolerances analysis problem to meet the required design specifications. The tolerances design for a linkage pivot is a modified and extended version from that given by Budynas et al. [7] and is as follows:

Project #1 Tolerances Design for a linkage pivot

A pivot in a linkage has a pin (shown in Figure 1) whose dimension $x \pm a$ is to be established. The thickness of the link clevis is 1.5± 0.005 inch. The designer has concluded that a gap between g_{min} and g_{max} will satisfactorily sustain the function of the linkage pivot.

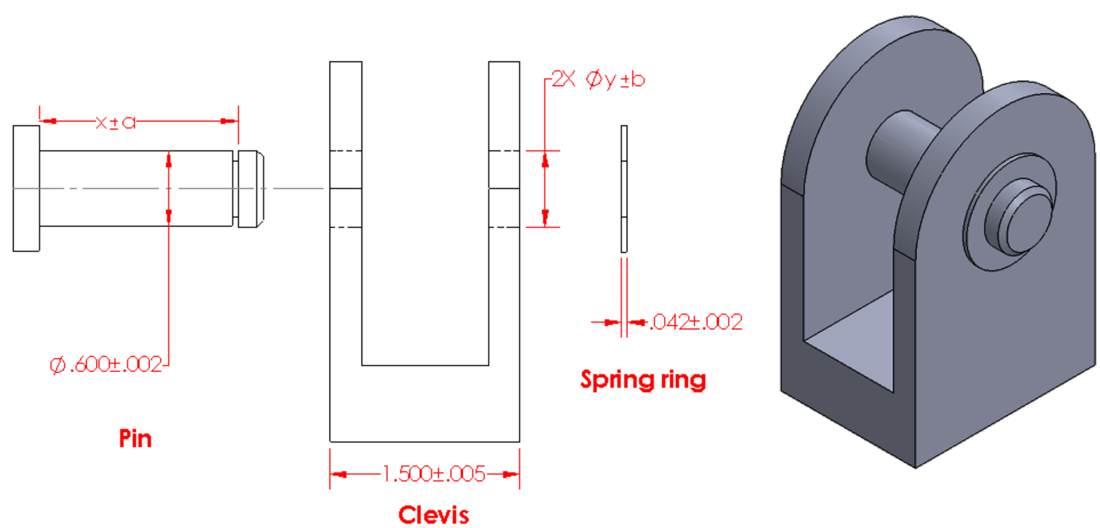

Figure 1. Linkage pivot

For interchangeable assembly processes:

A. Determine the dimension x and its tolerance a.
B. If the pin diameter available in the stock is 0.6 ±0.002 inch and M1 manufacturing process is used to create the clevis holes; Suggest an appropriate clevis hole diameter y to ensure the minimum clearance between the pin and hole is E. (Note: use typical tolerance limits b for M1 process, table 5.2 (or 5.4) in your textbook)
C. Use TolAnalyst© tool to verify your results in part A.

Notes:

i. g_{min}, g_{max} , E and M1 (b) values are assigned for each student.

ii. Show your analysis for the parts A and B precisely using both 100 percent and statistical interchangeability methods.
iii. Submit the tolerance analysis report for the part C in addition to your linkage pivot assembly and the part files.

The expected learning outcomes from this project are:

- Understanding the relation between engineering design of product and assembly process using tolerance analysis as part of the design specification.

- Implementing tolerance analysis for a specific product in x and y-directions using 100% interchangeability and statistical methods.

- Understanding the relationship between the tolerance and type of manufacturing process used to create different features in the components.

- Understanding and Using Tolanalyst simulation tool in SolidWorks to implement tolerance analysis for the assembly and compare the results with the traditional methods.

Project #2 Sand casting of a wolf head

This project is the first of a series of engineering manufacturing processes to create a nutcracker as a final project in this class. The first subproject is designed to provide students with a hands-on experience of the sand casting process of a wolf head shown in Figure 2. It is interesting that our engineering department is one of the few that still offer this real experience with the casting process using an in-school foundry. The students need to use design equations for heat and pouring concepts (Eq.1), and the solidification and cooling process analysis (Eq.2) [8]. Also, the students need to use the SolidWorks part file of wolf head to calculate the surface area and volume for the nonregular casting shape. Figure 3 shows the casting process in the department's foundry and the final casting product.

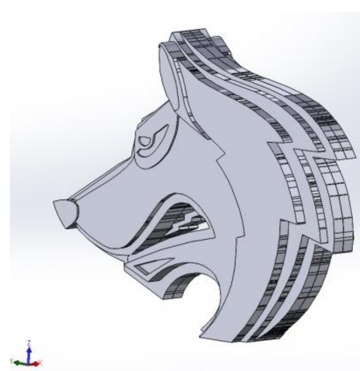

Figure 2. 3D CAD view for the wolf head casting project

1- Heating and Pouring

$$H = \rho V\left[C_s(T_m - T_0) + H_f + C_l\left(T_p - T_m\right)\right] \quad \ldots (1)$$

H = total heat required to raise the temperature to the pouring temperature [J],
ρ = density [g/cm^3],……….
C_s = weight specific heat for the solid metal [J/(g °C)], …………
T_m = melting temp. of metal in [°C],…………..
T_o= starting temperature of metal [°C],…………
H_f = heat of fusion [J/g],……….

C_l = weight specific heat for the liquid metal [J/(g °C)],…………
Tp = pouring temperature [°C], ……………..and
V = volume of metal heated [cm^3]…………………

Total heat required for pouring (H)=

2- Solidification and Cooling (<u>Chvorinov's rule)</u>

$$T_{TS} = C_m \left(\frac{V}{A}\right)^n \text{…………………….(2)}$$

T_{TS} = Total Solidification Time [min] ………..
V = volume of the casting [cm^3]………..
A = surface area of casting [cm^2]………..
C_m = mold constant [min/cm^2]…………
n = an exponent, usually n=2………….
C_m depends on:……………….

- Mold material
- Thermal properties of the cast metal
- Superheat (pouring temperature relative to the melting point of the metal)

Total solidification time (T_{TS})=

Figure 3 sand casting process and the final product

Results and Discussions

The assessment plan of the listed outcomes for the new teaching approach is measured directly using students' evaluation survey (class participation and critical thinking) and students' motivation in students' micro-lectures and projects. The direct evaluation result from class assignments is used to measure a knowledge increase related to the selected course topic. The academic feedback from other faculty members about course implementation strategy and the learning outcomes according to the ABET accreditation criteria is also considered in this study.

A pre-lecture survey is prepared to measure students' previous expectation of the course in general and teaching style in addition to some questions that can increase students' awareness about the selected topic (the dimensions and tolerances analysis in the assembly process). The survey results show that about 32% of students hate or dislike the traditional lecture style, 60% do not care and about 8% love the traditional lecture style. Also, it shows that about 85% of students do not know anything about tolerance analysis simulation tools in SolidWorks.

A post-lecture survey includes more specific questions about the new instructional components in the course, (students' micro-lectures and design based projects), in addition to knowledge development assessment questions.

In general, the student's feedback about micro-lectures (MLs) was very good. The most of students mentioned that they learned much or learned very much from the ML. The students were asked to write a piece of information learned from the micro-lecture topic (selective assembly and tolerances analysis). Here are some samples of student's answers ("*ISO has 3 standards, selective assembly is 100% interchangeability, and reduce machine time but increase cost*.", "*The limitation of selective assembly slide was become new information to me. Normal distribution was expected, however, I think it would been hypergeometric. It was interesting that selective assembly was used since in 1930's*.", "*allows for 100% interchange with the cost effectiveness of statistical*". The student's feedback shows increased knowledge and advanced thinking about the subject. The effectiveness of the micro-lectures is studied from the studies perspectives, thus about 65% like and about 12% dislike MLs. These results show a strong shift in student's perspective on lecture style from the pre-lecture survey. The following is some interesting feedback from students about why they like MLs: "*They are interesting and help me improve instruction skills, they also teach me a lot* ", "*It spices up class and makes it fresh* ", " *Improves public speaking and presentation skills. Also makes you study certain material in greater depth.", "gives us a heads up to the topics before lecture* ", "*they help the class learn and interact in class* ", "*it is a good change in pace and keep students engages. It is difficult to stay engaged when you have 4+ hours of class in the same room, so mixing things up is good*". Also, here are some ideas about why the students dislike the SMLs: "*I feel that individual student may learn more, but the class probably doesn't*." *You are asking students to be an "expert" on the subject and be able to "teach,"*". All positive and negative notes show the importance of improving independent and lifelong learning skills through active learning strategies through class participation and discussions.

For the MLs related to the casting topics the peer evaluation survey for the casting processes listed in Table 1 show that more than 80% of the students in the class (24 students) learned or learned much from the micro-lectures. Again, the students were asked to write a piece of information learned from the MLs topics (sand casting, refractory casting, vertical casting, die casting, investment casting and centrifugal casting). Here are some samples of student's answers *"die casting has good dimensional tolerances, centrifugal casting can make giant symmetrical products, vertical casting eliminates trimming.", "die casting is cost-effective with high volume* *demand, especially with metals with low melting points.", "Investment casting has nothing to do with financial aspects like the name would suggest. It's actually a wax form casting.", " die casting has good dimensional tolerances, centrifugal casting can make giant symmetrical products, vertical casting eliminates trimming.", "Centrifugal casting is used in most aircraft, dams, and military products, Die casting is only cost-effective with high volume demand, in vertical casting produce parts with high quality, eliminate trims, quicker molds, reduce cycle time. Refractory anchors are designed to expand to allow the mold to form."*

For the in-class Project #1, 75% of the students were able to solve part A successfully, about 67% of the students were able to solve part B successfully, and about 71% of students used simulation tool (Tolanalyst©) successfully to verify their results from the traditional tolerance analysis of part A. These results aligned with the students' feedback in the post-lecture survey which shows that 95 % of the students think that the in-class project helped them enrich their understanding of the class topic. Also, more than 62% of students are willing to use the simulation tools in their future work in the industry in addition to 35% that may use it. The post-lecture results show that introducing new simulation tools are very appreciated for their future career as engineers and this is a good outcome compared with the pre-lecture survey which shows that about 80% of students in this class do not know the simulation tool Tolanalyst© in SolidWorks. Also, about 80% mentioned that working on the in-class project enriches their understanding of the topics. It is interesting to note that adding simulation tools to the project assignment does not require a considerable amount of time from the students. According to the post-lecture survey, about half of the students spent 2 hours and about 27% of students spent 4 hours to learn Tolanalyst© tool. Some students struggled with the simulation part of this project due to their lack of some basic SolidWorks skills.

For the Project #2 Sand Casting, it was interesting to see that most of the students can connect the theoretical casting process analysis with the experimental results for the wolf head casting. Also, they are able to determine the required variables and parameters to complete their analysis and to justify some of the sources of errors using a scientific and engineering approach. Besides, the students understood how it is essential to use the single accurate database form the CAD system to complete the design and manufacturing processes accurately. Some students wrote the following in their reports: "*Theoretically, the casting would take 9.33 minutes to totally solidify, but during the experiment, we noticed the casting took about 15 minutes to solidify. This was due to the unknown values used in the equation as well as the estimates. The values that were estimated were not completely accurate. For example, the mold constant is not entirely accurate and cannot be accurately assumed as there are too many variables to consider. Also, the impurities in the aluminum used greatly affected the cooling time as well as the pouring and shrinkage.", "Overall, the experiment was a great learning experience for how casting works in the real world in comparison to the classroom. The equations used in the classroom do not directly transfer to the experiments. .....Not only did we learn the process but we learned the safety issues and extra steps involved in casting that aren't taught in the classroom. Also, the lab helped us to understand the work that is behind some of the objects we use in everyday life and how difficult it can be to* *make them perfectly. Not to mention the memories made, with the thunder wolves being our mascot, we got to make an item to remind us of our college years.", "overall I think this was a very successful lab and I felt as though I could really connect what I was learning in the class to what we were doing in lab. I felt much more comfortable on the test because of my experiences in the lab. I am a very visual leaner and the lab has helped me understand the information much more.", "The casting itself was very interesting.... the casting was done well when the vents and riser filled evenly….The experimental and theoretical analysis is more likely off by a pretty big factor. The main source or error came from error in calculating the correct volume and surface area of the casting. This experimental analysis did however give insight on how real world parts are made.", "After having hands on experience with sand casting, I have a better understanding of the procedures and process needed to make a casting from a mold. ".*

Conclusions and Lessons Learned

First, using students micro-lectures helped in improving students' life-long learning and communication skills (ABET Criterion 3. Student Outcomes: 3 and 4). **Second,** students' micro-lectures increased students' learning outcomes by making the class more interactive. **Third**, the simulation-based design project and hands-on projects helped in enriching students' understanding of the studied topic and improve their ability to deal with real-world problems and analysis and use their engineering judgment to draw conclusions (ABET Criterion 3. Student Outcomes: 6). **Forth**, introducing simulation tools as a part of the learning environment can be implemented easily and without burdening the students much, especially if they already used the same CAD system as a drafting and design tool. A single CAD database can be used to produce many types of drawings and models used throughout the design and manufacturing processes.

The suggested teaching strategy can work effectively with small size class and maybe to middle size if the instructor (s) can provide adequate resources. For the future work the authors are planning to introduce more simulation-based projects in the curriculum like machining simulation and cost analysis of casting.

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