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Focused Curricular Activities Designed to Improve Student Competency in Data-driven Process Improvement

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Focused Curricular Activities Designed to Improve Student Competency in Data Driven Process Improvement

Abstract

Recent internal assessment and evaluation activity within the Mechanical Engineering Technology (MET) program at Montana State University (MSU) identified an opportunity to improve student learning outcomes regarding knowledge and application of statistical concepts. Since the MET program did not have room for an additional course in this area, the curricular review identified an existing design and build course where specific activities could be developed and integrated to provide students exposure to additional statistical material. Specific course changes were made through the addition of lessons focused on understanding the concepts of Statistical Process Control (SPC) and Design of Experiments (DOE). Focused laboratory activities incorporating use of a Coordinate Measuring Machine (CMM) were developed and implemented to reinforce the additional lessons presented in the lecture component of the course. Ultimately, these lessons and lab activities provided a deliberate and pointed educational focus designed to improve achievement of essential statistical competencies, especially those related to data collection, data analysis, and drawing appropriate inferences from the results of the analysis to improve processes. Upon completion of these lessons, increased competency and comfort with the practical application of statistical practices is expected. This paper outlines the assessment activity that identified the opportunity, explores how the pedagogical approaches used in the selected course were developed to enhance and improve students' knowledge of statistical applications appropriate to the MET profession, reports on initial results of this implementation, and finally, identifies future improvements to the approach.

Introduction

Curriculum development is a constant and continually developing field of study. The goal of any academic organization is to continually improve the overall quality of the education they deliver to their students. To this end the curriculums these programs deliver should be in a constant state of improvement. One of the methods by which Montana State University (MSU) works towards this goal is through accreditation of its Mechanical Engineering Technology (MET) program with ABET. To maintain accreditation, the program must define outcomes, assess those outcomes, evaluate how well those outcomes are being attained, and finally, continuously improve the program. To satisfy ABET defined Criteria for Accrediting Engineering Technology Programs, 2019-2020 the MSU MET program has adopted student outcomes listed as #1 through #7. The focus of this work is Student Outcome #6: "An ability to conduct standard tests, measurements, and experiments and to analyze and interpret the results to improve processes." This outcome was noted in prior assessment activities at MSU as an area for improvement. For assessment purposes, the program has defined four competencies that provide greater specificity to Outcome #6. Competency 1 calls for students to be able to "Develop an experimental plan to answer a specific question or test a hypothesis." Competency 2 requires students to have the ability to "Collect data appropriate to the experiment or test." Competency 3 requires students to be able to "Analyze data collected using appropriate methods." And finally, Competency 4 requires students to "Draw appropriate inferences from analysis results to improve processes."

To improve student achievement of these competencies, lessons in Statistical Process Controls (SPC) and Design of Experiments (DOE) were designed and added to the ETME 415 – Design for Manufacturing and Tooling course. This is a senior level required course in the MET program. Comfort with statistical applications is increasingly vital in the role of the modern mechanical engineer due to the increased commonality of practical statistical tools in industry. This requires the complete understanding and effective practice of all aforementioned competencies. In a field of study that is constantly finding increasing amounts of data is attainable and available, the contemporary engineer must be able to utilize that data with appropriate methods to make informed decisions.

This paper describes the academic approach used to create the common foundation of statistical comfort that is required to create engineers who not only understand relevant statistics, but are also confident in their practical application. It is the goal of the authors that through concise curriculum development and use of practical examples these program outcomes will be translated into student competencies.

Overview of the Literature

Engineering curriculum development is a rapidly moving field of study. Administrators and faculty are constantly altering, updating and improving curricula in order to create an educational program which prepares students to be relevant in a dynamic world. Fast-paced technological developments inevitably lead to program level and curriculum level changes. These changes come in many forms, such as adding new courses [1], improving assessment methods [2], or increasing realism in academia in order to create more well-rounded engineers [3]. Unfortunately, curricular change in engineering and engineering technology programs has traditionally happened very slowly [4]. Maintaining relevancy is important for all fields of education, but is especially so in engineering and engineering technology programs [2]. The Mechanical Engineering Technology (MET) profession and those who study it must be prepared for a future industry consisting of more dynamic working requirements, often centered on data heavy topics such as nanotechnology and biotechnology, energy and environmental issues, and a myriad of other data-driven developments [5]. These areas must also be considered alongside the importance of economic growth balanced with sustainable growth [6].

Many engineering and engineering technology programs choose to be accredited to provide a measure of quality to the program. Accreditation organizations, such as ABET, provide specific criteria related to student outcomes which colleges and universities can then use as a guide to measure quality and ensure continuous improvement of their programs. In conjunction with the institution of these accreditation agencies, significant research has been done in terms of translating those requirements into actionable steps, creating guidance for targeting learning objectives, identifying instructional techniques with which to complete those objectives, and the development of strategies to integrate course-level activities which align with those instructional techniques [7]. These course-level activities are derived from the accreditation objectives as well as instructor and program goals to form the instructional material [7]. From there, course-level activities are developed from a topic to a full exercise or lesson depending on factors such as program capabilities and learning style of the students. Collaborative, active, and problem-based learning are common in MET specifically, and engineering in general and discovering which one or what combination should be pursued in order to achieve the desired learning objectives is what ensures student comprehension [8].

Many models exist in which these learning styles, and thus the requirements for learning, can be organized. For example, Bloom's Taxonomy is a commonly used model for defining educational objectives [8]. These models can help the path to the overarching objective become clearer. However, these models will not support reaching the educational objective if the instructional techniques or teaching methods are inadequate. Modern engineering programs are presented with a laundry list of requirements needed to create competent and relevant contemporary engineers. This list is unattainable in the allotted duration of study if courses continue to be structured as separate, disconnected, entities [9]. Some research proposes combining topics in semi-related courses in order to both streamline the program and relate relevant topics. In order to do this, courses must be structured according to clear objectives, around relevant material, with a balance of information, incorporating active and cooperative learning, which would then promote and allow challenging examinations, all the while providing an environment which shows concern for student learning [9]. Structures such as these can be used to organize the program. This will allow students to begin to develop the critical skills that will translate to the desired learning objectives [10]. Whereas the course-level work and the instructional techniques focus on what some would call technical skills, in order to achieve proficiency in the overarching objectives, students must also develop professional skills in tandem with their practical and technical knowledge. This includes skills such as general problem solving, writing, teamwork, self-assessment, and change management [10]. These abstract skills serve as a scaffolding to support practical and technical skills and knowledge in context. Promoting the development of the professional skill type is inherently more difficult and centers back on course and institution culture more than actual curriculum topics [10]. Even so, there are models by which these skills can be incorporated into curriculum, or at least stoked in some way. Woods outlines eight activities which can be used to promote these skills in curriculum. They include: identifying objective relevant skills, conducting actual research on the extent of said skills, making explicit the behaviors associated with those skills, creating activities which promote those behaviors, encouraging monitoring of those behaviors, encouraging reflection of those behaviors, grading the process as a whole not only the result, and using a standardized assessment to do so [10]. Researchers and teachers using these methods can create relevant, dynamic, impactful, and value-added changes to their curriculum, the approach leveraged in this work.

Study Methods

Felder and Brent's 2003 article [7] defines a model by which to create course material based upon accreditation requirements. The model is summarized in Figure 1.

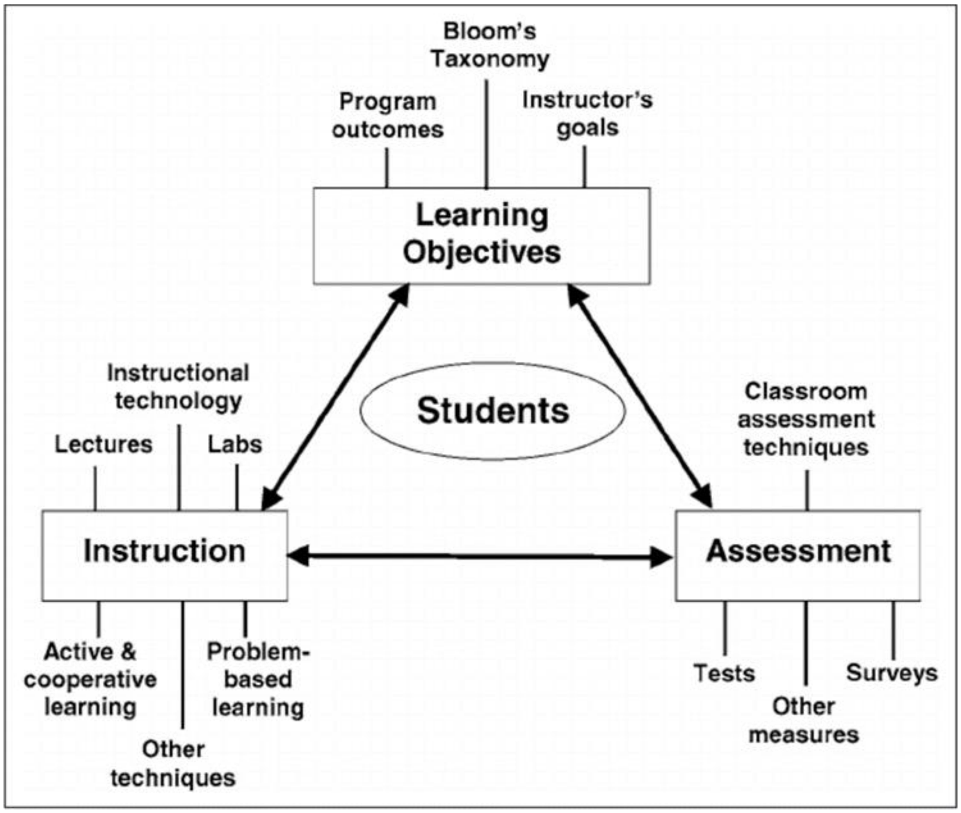

Figure 1: Elements of Course Design [7]

From the defined model and as shown in the figure, course improvements are a continuous cycle of learning objectives, instruction methods, and assessment techniques. These defined learning objectives are created by instructor goals and program outcomes and categorized by organizational methods such as Bloom's Taxonomy. Those objectives then reciprocally influence instruction methods in terms of lectures, labs, and defined learning styles. Those instruction methods require specific assessment techniques such as tests, surveys, etc., which then influence learning objectives and instruction. This cycle continues with these various assessment techniques influencing learning objectives by either the quantified attainment of defined program outcomes or of instructors' goals. Often, the assessment methods are defined by the objectives themselves. In short it is a continuous cycle of bidirectional influence centered around the students.

In this application the learning objectives supporting accreditation activities are defined to allow assessment and evaluation using competencies defined as part of the MET continuous improvement process. The better understand the competencies of interest, we provide further definition here:

- Competency 1 - "Develop an experimental plan to answer a specific question or test a hypothesis." This means the students should be able to form a coherent solution to a problem and then be able to design an experiment to test their solution.
- Competency 2 - "Collect data appropriate to the experiment or test." This means students can decisively select the required data for the designed experiment.

- Competency 3 - “Analyze data collected using appropriate methods.” This means students can confidently select a viable analysis method which will aid in proving – or disproving – their solution from their selected data.
- Competency 4 - “Draw appropriate inferences from analysis results to improve processes”. This means students can make practical decisions based on the results of the selected analysis method.

Additional objectives related to these competencies come in the form of the instructor’s goals to expose the students to additional aspects of the design and inspection process and to clarify existing lessons. Within the MET curriculum at Montana State University these competencies relate heavily to inspection (specifically inspection based upon design), and application of practical statistical knowledge. These instructor goals coupled with the defined accreditation objectives provide the framework for the creation of course instruction material.

The course selected to incorporate these accreditation activities was ETME 415 – Design for Manufacturing and Tooling, a required MET senior level course and a popular Mechanical Engineering (ME) elective course. Within this course, students already examine various inspection methods and some practical statistical methods. To expand on both of these areas of learning and to enable the assessment objectives, the instructional team in charge of the course decided to create new material in the form of lectures, labs, assignments, and reading focused on Statistical Process Controls (SPC) and Design of Experiments (DOE).

SPC is a group of analysis tools used to qualify performance and capability for any process. Under the realm of SPC the lessons explored various control charting tools including X-BAR chart variants and numerous other situation specific charting methods. Process capability methods including C_p and C_{pk} were also explored, as well as measurement system verification using Gauge Repeatability and Reproducibility (Gauge R&R). SPC was chosen as a focus because of its common use in industry and its applicability to a wide range of physical and non-physical processes. This new module included original literature, a lecture, and an assignment which were created in concert with one another to build a fluid connection between components of the module. The SPC module is targeted to achieve the assessment objectives of Competency 3 (C3) and Competency 4 (C4). These accreditation objectives are targeted because SPC is mainly an analytical tool with which to make practical inferences on process improvement based on existing data. The remaining assessment objectives focus on forming a hypothesis, creating an experimental plan to test that hypothesis, and collecting data related to the plan and hypothesis. Since SPC relies mainly on existing data and is more of a reporting method than an experimental model, an additional module for DOE was created to achieve these remaining assessment objectives, and to satisfy the instructors goals for the course.

Design of Experiments encompasses goal oriented statistical experiment design in which the practitioner is seeking to explore potential influential factors on a given response [11]. DOE is a statistical framework created from situational requirements in which a response is measured while varying a number of factors each with two or more realistic and representative levels. The replicated measurement of the response of various treatments (the certain settings of prescribed levels) is then inputted into an Analysis of Variance (ANOVA) model. This ANOVA test then provides the practitioner with numeric as well as descriptive statistics defining the rank and significance of effect of the selected factors and levels on the response. In this module, a recorded lecture, a new laboratory experience, and an assignment were created. The DOE module targets the remaining assessment objectives of Competency 1 (C1) and Competency 2 (C2). DOE was selected for these objectives because it is heavily focused on the hypothesis development, experimental plan, and data collection points. The laboratory exercises also cover data analysis and interpretation, which could also target C3 and C4. However, since SPC covers those topics more directly, the focus of the DOE module is to satisfy C1 and C2. Introduction of DOE also enabled the incorporation of additional educational components. Specifically, in the DOE lab, students explore the effects of various manufacturing processes on the Geometric Dimension and Tolerancing (GD&T) specification of cylindricity. Additionally, the response measurement for the DOE exercise is taken by a Coordinate Measuring Machine (CMM). Incorporating the GD&T and CMM components into the DOE lesson not only aids in addressing the remaining accreditation objectives but also supports instructor goals of exposing students to additional aspects of the design and inspection process through use of the CMM) and clarifying existing lessons through the visualizing GD&T features. Additionally, by incorporating multiple instructional elements, the DOE module provides a very time effective use of limited lab time.

Thus far, the learning objectives and instructional methods have been identified. Now assessment techniques must be defined. The assessment of this new material is broken into two components: graded assignments and a survey on students' statistical comfort deployed before and after the SPC and DOE modules. The actual assignments created with the DOE and SPC modules were designed to achieve the respective targeted accreditation objectives (SPC: C3 & C4, DOE: C1 & C2). The assignments are made up of various questions on the topic at hand as well as specifically targeted questions designed to point directly towards the accreditation objectives. The assignment and post module quiz provided an academic assessment for the student in each module. Additionally, targeted assignment questions were used for additional assessment using an ABET competency rubric developed as part of the overall MET Program Assessment Plan. This data will be included in future evaluation of the accreditation requirements.

The second assessment component is a survey instrument. The same survey is given before and again after the two modules are taught providing comparison data pre and post intervention. The goal of this survey is to gage student comfort with the topics discussed in order to determine if the lessons had any impact on the students in terms of how comfortable they are with the required competencies. The survey is organized into ten Likert scale (1 – 5) questions, four of which relate directly to the accreditation objectives, and the remainder of which support components of those objectives. For example, C1 is concerned with hypothesis and experimental plan creation. The targeted survey questions for C1 asks if students are comfortable creating an experimental plan to test a hypothesis. The first supporting question (for the C1 targeted survey question) ask students to gage comfort with creating a hypothesis itself, while the second asks students to gage their comfort with creating an experiment plan itself. The responses to these pre and post survey questions directly support the assessment of the accreditation objectives. Student comfort considers how comfortable a student feels in the classroom. Developing comfort begins with student experiences with classmates and instructors and results in the student's comfort level with the material being discussed in the course increasing. A higher comfort level with a certain material leads to higher competence in said material [12]. The survey component of the assessment program is meant to investigate this comfort level. The layout of these assessment components can be seen in Figure 2. Through the survey presented both before and after the additional modules and through the targeted assignment questions, a sufficient and representative assessment technique for the accreditation objectives is created.

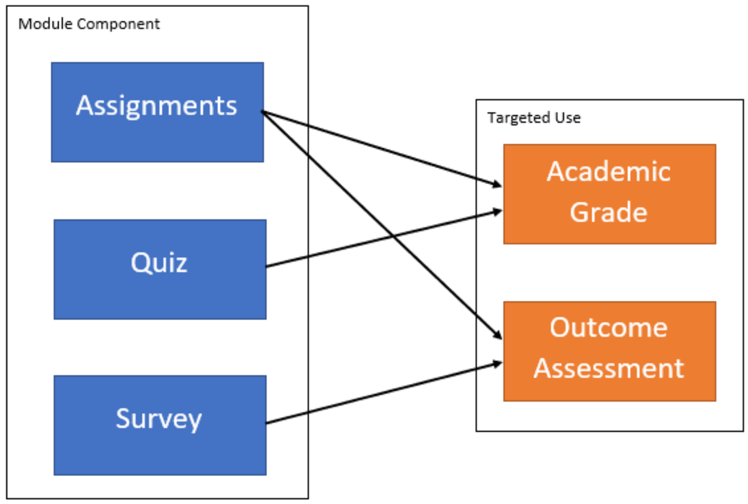

Figure 2: Assessment Model

Classroom Results

The assessment methods discussed in the previous section frame the main results of this research. The goal of this study is to gage achievement of the specified student outcomes in support of ABET accreditation. To that end, this section discusses the results of the assessment techniques used to measure performance of that achievement. The two methods of assessment used for these accreditation objectives were the targeted questions within the two module assignments and the pre and post surveys.

Over the course of this effort, a SPC and DOE module were added to the course curriculum. The SPC module was added in the initial semester (Fall 2019). The DOE module was added in the following semester (Spring 2020). The modules were not introduced in the same semester as the DOE module included a lab component which required additional time to create. This means that data from SPC assessments exists for three semesters (F19, S20, & F20) and data for DOE exists for two semesters (S20, & F20). Additionally, survey data only exists for the final semester (F20) of the study as the development of the survey was delayed by to the unforeseen push to move to a virtual curriculum in the second half of the Spring 2020 semester on account of the COVID-19 global pandemic.

In the pre and post surveys administered before and after the two additional modules were conducted, students were asked to self-judge their comfort level with practical statistics. From the results of these surveys we can see that the student body as a whole gained significant ($\alpha \leq 0.05$) comfort with the material. This is shown in the increase in average response of each of the competency-related survey questions and the results of the comparison between the pre and post test scores made using a 2-sample t-test in Minitab 19. This shows that after the modules, in each question asked, students were more comfortable with the competencies. Summarized results from the surveys are provided in Table 1. The questions for the pre and post surveys can be seen in Figure 3. These questions were given in the same order pre and post lesson and answered on a

Likert Scale where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree.

Student Comfort Survey Results

	Average Score		T-test
Question (competency)	**Pre**	**Post**	**p-value**
Question 3 (C1)	3.67	4.47	<0.001
Question 5 (C2)	3.82	4.47	0.002
Question 7 (C3)	3.39	4.32	<0.001
Question 10 (C4)	3.88	4.58	<0.001

Table 1: Pre and Post Module Survey Results

1. I feel comfortable defining a hypothesis for a given problem
2. I feel comfortable defining variables involved in a given problem
3. I feel comfortable developing an experimental plan to test a hypothesis
4. I feel comfortable knowing the level of data accuracy and precision required for the experiment
5. I feel comfortable collecting appropriate data for an experiment
6. I feel comfortable selecting a relevant data analysis method
7. I feel comfortable applying data analysis methods
8. I feel comfortable analyzing the results of a data analysis method
9. I feel comfortable proving or disproving my hypothesis based upon the results of an experiment
10. I feel comfortable drawing practical conclusions based upon my understanding of the results of an experiment

Figure 3: Pre and Post Survey Questions

In assessment of the targeted questions from the three semesters of SPC module assignments and two semesters of DOE module assignments, students generally exhibited an acceptable proficiency in the practical statistical competencies outlined in the ABET competency rubric. The rubric is provided in Table 2. Rubric values were assigned to student work in tandem by the course instructor and course teaching assistant. Each individual ranked the student's work and differences were discussed until a consensus on assigned value was reached. This was done for both semesters of DOE and all three semesters of SPC. To determine whether student's achieved adequate proficiency, each competency in each semester was tested using a one sample t-test in Minitab 17. These tests were run comparing the student scores against a target mean of 3.0, as outlined in the rubric. As shown in Table 3, for the final semester in both the SPC and DOE related measures, students achieved competency (failure to reject the null hypothesis) for almost every measure. This was not the case for most outcomes in the initial semester of measurement. More importantly, these levels of performance were not achieved before these modules were developed and implemented, the very reason for this study.

	Levels of Attainment				
Competency	**4 Exceeds Expectations**	**3 Meets Expectations**	**2 Below Expectations**	**1 Unsatisfactory**	**Rating**
Develop an experimental plan to answer a specific question or test a hypothesis.	• The plan completely and concisely defines the question or hypothesis to be tested. • The plan clearly defines all dependent, independent and control variables. • The plan includes a complete list of the equipment and materials needed. • The plan explains all elements of the set-up required. • The plan fully outlines the procedure to be followed, including data collection protocol and safety precautions.	• The plan mostly defines, with few exceptions, the question or hypothesis to be tested. • The plan defines, with few exceptions, dependent, independent and control variables. • The plan includes a mostly complete list of the equipment and materials needed. • The plan explains most elements of the set-up required. • The plan outlines, with few or minor detail omissions, the procedure and safety precautions to be followed.	• The plan provides insufficient definition of the question to be answered or hypothesis to be tested. • The plan is missing required definition of dependent, independent and control variables. • The plan fails to identify and list some of the equipment and materials needed • The set-up explanation is incomplete or inaccurate • The procedure outline is missing important elements.	• The plan provides little to no definition of the question to be answered or hypothesis to be tested. • The plan is missing most definition of dependent, independent and control variables. • The plan fails to identify and list most of the equipment and materials needed • No set-up explanation is included • The procedure outline is missing.	
Collect data appropriate to the experiment or test.	• The data is complete and of appropriate accuracy, precision and unbiased amount to answer, without error, the question or hypothesis being tested. • The data is verified and documented properly.	• The data is of appropriate accuracy, precision and unbiased amount to answer, with few errors, the question or hypothesis being tested. • The data is partially verified and documented properly.	• The data lacks appropriate accuracy, precision and unbiased amount to answer the question or hypothesis being tested. • The data is not verified or documented properly.	• The data is not of the appropriate accuracy, precision and unbiased amount to answer the question or hypothesis being tested. • The data is neither verified nor documented properly.	
Analyze data collected using appropriate methods	• The analysis method selected is most appropriate for the data collected • the method is applied correctly.	• The analysis method selected is appropriate for the data collected • the method is applied with few errors.	• The analysis method selected is not appropriate for the data collected, and/or the method is applied incorrectly.	• The analysis method selected is not appropriate for the data collected.	
Draw appropriate inferences from analysis results to improve processes	• The interpretation of the data and conclusions drawn are completely consistent with the analysis results.	• The interpretation of the data and conclusions drawn are mostly consistent with the analysis results.	• The interpretation of the data and conclusions drawn are not consistent with the analysis results.	• No ability to interpret the data and form conclusions was demonstrated.	

Table 2: ABET Competency Rubric

	Semester Average		
Competency (method)	**F19**	**S20**	**F20**
C1 (DOE)		2.55**	2.76*
C2 (DOE)		2.76*	2.92
C3 (SPC)	2.59**	2.60**	2.97
C4 (SPC)	2.67**	2.89	2.89

* - $\alpha \leq 0.05$, ** - $\alpha \leq 0.01$

Table 3: Average Competency Rubric Scores by Semester with p-values

While comparing the averages between semesters showed no statistical difference ($\alpha = 0.05$) there is a gradual increase over the three semesters. This is likely due to increased instructor proficiency and familiarity with the lessons themselves, resulting in an increased ability to impart the required knowledge.

From the results of the accreditation objective based pre and post surveys, as well as the targeted module assignment questions assessed with the ABET competency rubric, we can see that students have increased competency with the required accreditation objectives and the efforts of continuous improvement have been successful despite the challenges of implementing these changes during a pandemic.

Discussion

Development of these additional curriculum modules followed the structure outlined by Felder and Brent [7] described in the methods section of this paper. The motivation for these curriculum improvements came from changes in learning objectives caused by updated accreditation requirements specified by ABET. These updated requirements were catalytic in starting this change, but other factors also played a key role. Instructor objectives for this class curriculum change were described as the intent to "expose the students to additional aspects of the design and inspection process and to clarify existing lessons." These instructor objectives stem from the desire of any and all instructors to increase students competence and comfort with whatever lesson is being administered.

In this case the lesson being administered is one of applied statistics. To that end, exposing students to additional aspects of the design and inspection process and clarify existing lessons within the frame of the required accreditation objectives is intended to increase student competence and comfort with practical statistics. The targeted module assignment questions focused heavily on measuring competency while the pre and post survey questions focused primarily on measuring comfort. In the module assignments students were asked to work through problems and provide insightful answers to application questions that require acceptable competency of practical statistics. In the pre and post surveys, questions were phrased to elicit a self-examination from students as to their comfort level with practical statistics. Thus, the assessment methods were designed to do more than simply rate students quantitatively, an intended overarching qualitative assessment was designed-in to gage these core learning objectives.

Qualitative metrics are inherently more difficult to assess, this instance is no exception. From the results presented in the previous section, we can see that the accreditation requirements were indeed achieved based on robust quantitative measures. Examining the qualitative assessment requires more discussion. This assessment centers around the students' ability to extrapolate from lessons to real world applications. This can be done through the development of professional skills. Through this effort, along with evidence from the literature [10], it was found that developing the scaffolding of these professional skills around the core technical skills comes from the communication of the lessons: how they are presented, how points are made, and how questions are phrased. The ability to do this comes from experienced teachers who have mastered not only the subject matter but the art of teaching itself, or for those who are not yet masters of the art, from practice with the lessons. Evidence of this impact can be seen in the improved results of the targeted module assignment questions over the multiple semesters data was collected. The steady improvement of student competency from unaltered lessons and assignments supports this idea. The instructor's increasing proficiency with the subject, not technical proficiency (which is required) but proficiency in teaching, builds the scaffolding for the students to learn competency and gain comfort with the technical skills. This then leads to students developing the ability to relate the lessons to real world applications, the true end goal.

Conclusion

This paper has explained the systematic process of course curriculum changes within an accredited MET program. These changes were in response to updated accreditation requirements from ABET for all accredited MET programs. These objectives were examined and instituted along with instructor objectives in the form of two additional lessons, or modules within the ETME 415 – Design for Manufacturing and Tooling course. These modules were created using curriculum development frameworks from the literature in order to achieve the best possible application of the required accreditation and instructor objectives. The results from this application were then reviewed to determine if (1) the accreditation and instructor objectives were met, (2) if students gained competency and comfort with the application of practical statistics, and (3) if students developed an ability to extrapolate from the lessons to real world applications. This work achieved all three of these items.

However, there are some shortcomings or limitations in this work. First, these modules were implemented over the course of the global COVID-19 pandemic which has presented challenges across all of society. The impact was that in some semesters, many of these lessons and labs were administered virtually, both synchronously and asynchronously. This change in the delivery usually has a negative impact on the effectiveness of lessons. These lessons are not immune to that impact. Future research will focus on tailoring these and all modules to the blended learning delivery system with which we are now faced.

To that end, the project is currently ongoing and specific aspects of the modules designed and introduced to the course in question will continue to be adjusted to better facilitate learning. The core concepts of the modules as realized through the methods discussed will remain the same, but future research will focus on continuing to tailor the learning delivery system. This will not only improve the lessons themselves but will require considered practice of the lesson delivery, which will echo the sentiments of the previous section in building said instructor's proficiencies in teaching this material.

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