The Impact of Active Learning Interventions on Student Outcomes in Core Mechanical Engineering Topics

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Myela Autumn Paige

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The Impact of Active Learning Interventions on Student Outcomes in Core Mechanical Engineering Topics

Approved by:

Dr. Katherine Fu, Advisor
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Gordon Kingsley
School of Public Policy
Georgia Institute of Technology

Dr. Hang (Jerry) Qi
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Ruth Poproski
Center for Teaching and Learning
University of Georgia

Dr. Aldo Ferri
School of Mechanical Engineering
Georgia Institute of Technology

Date Approved: December 8, 2021

To my mother, Pamela Paige, and my father, Shelby Paige, Sr.

Without the love and push of you two, this wouldn't have been possible.

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LIST OF SYMBOLS AND ABBREVIATIONS

GD&T	Geometric Dimensioning and Tolerancing
PBL	Problem-Based Learning
FCF	Feature Control Frame
CMM	Coordinate Measuring Machine
MMC	Maximum Material Condition
LMC	Least Material Condition
3D	Three-Dimensional
τ_b	Kendall's t-coefficient
τ_{allow}	Allowable shear stress
τ_{max}	Maximum shear stress
γ_{max}	Maximum shear strain
φ	Angle of twist
φ_{allow}	Allowable angle of twist

SUMMARY

This research focuses on the enhancement of the undergraduate education in mechanical engineering using active learning techniques, and specifically, hands-on learning through the incorporation of student interaction with 3D multi-material printed and machined parts. Hands-on learning has been shown to be an effective way to not only improve student learning and engagement, but also as a means to retain students within engineering majors, importantly including members of underrepresented groups, such as women students. Complex subjects that impact a person's ability to apply knowledge in many different industries are mechanics of materials and geometric dimensioning and tolerancing (GD&T). Many core undergraduate curricula teach mechanics of materials in a highly theoretical manner, mostly using paper textbooks, which include textual definitions and descriptions of key concepts with illustrations to communicate material or structural behavior in given cases. GD&T is not as widely taught but is often taught in the same manner. While the traditional approaches to teaching these fundamental concepts may be sufficient for most students, they do not allow students to develop an intuition for the behavior of materials or manufacturing procedures, and do not foster strong retention of the knowledge acquired in the course. A method has been developed to improve attributes of self-efficacy, student satisfaction, and course performance by incorporating multiple active learning-based modules into the classroom. The following research questions are addressed within this dissertation research:

1. *In what ways can a more hands-on learning approach to teaching mechanics of materials and GD&T enable deeper student engagement and stronger retention of concepts?*

2. *How can new techniques in pedagogical design be incorporated to improve student learning and foster an engaging environment in mechanical engineering classrooms?*
3. *How can 3D printing and machining technology-driven active learning modules effectively enhance student engagement and conceptual learning in mechanical engineering topics?*

The main goal of this research is to provide instructors with active-learning modules to add value to topics that are crucial to the academic and career development of mechanical engineers. This dissertation is comprised of two distinct engineering education development projects. Both projects provide insight into the impact of hands-on module development, active learning, and spatial tools on student performance. The first project is mechanics of materials module development for four major topics in the course and the evaluation of the impact of the modules on the students. This development process was vital to understand how the combination of curriculum activity structure, 3D printed multi-material models, and participant feedback can shape the engagement and reception of the learning activities. The second project focused on the development and evaluation of an intervention for geometric dimensioning and tolerancing using machined parts and measurement devices, based on best practices learned from the development of the mechanics of materials modules. The evaluation of the performance of the student participants in the GD&T intervention revealed the impact of a subject-specific intervention in manufacturing on the absorption of key concepts by students. Data has shown that the interventions introduced in the classrooms helped increase the self-efficacy, performance scores, and satisfaction of students in both core topics in mechanical engineering. This pedagogical approach is applied to various engineering topics to understand the impact, effectiveness, and the flexibility in the active learning-based approach. The development of these activities revealed strategies for iterative design of hands-on learning activities for core engineering subjects in the undergraduate curriculum that foster engagement, encourage spatial conceptualization, and create an alternative modality for students to experience a different type of learning outside of traditional lectures.

CHAPTER 1. MOTIVATION

Deformable Bodies, also known as mechanics of materials, teaches engineers the fundamentals of how to design any type of structure to be safe, whether that structure is a bridge, a submarine, an antenna, or even a chair. The built environment, which many people take for granted as safe and well designed, hinges on the engineers' understanding of mechanics of materials to ensure reliable, resilient, and robust design. Currently, most core undergraduate curricula teach mechanics of materials in a highly theoretical manner, mostly using paper textbooks, which include textual definitions and descriptions of key concepts, with illustrations to communicate material behavior in given cases.

Similar to mechanics of materials, geometric dimensioning and tolerancing is a topic where students struggle to apply the complex concepts, but the material is crucial for an engineer who will be moving into a manufacturing or engineering design career. The rationale behind the work explored in this dissertation is that while the traditional style may be familiar to many students, it does not allow students to develop an intuition for the behavior of materials or applications of concepts and does not foster strong retention of the knowledge acquired in the course. By taking advantage of the growing popularity of 3D printing technologies and machining, students can experience a much more memorable, enjoyable, and engaging pedagogy of mechanical engineering concepts. They will have a deeper understanding of the core curriculum underlying their engineering program, setting them up for future success in more complex topics that build upon these foundational concepts.

The goal of this research is to facilitate active learning through a different pedagogical approach outside of the traditional lecture-style in mechanical engineering – hands-on modules using 3D printed and machined parts. It is assumed that converting mechanical engineering theory into real-life visualizations and implementing student exercises in certain classes will cultivate a different type of learning environment. Although studies have been conducted about more interactive activities in mechanical engineering, the approach covered in this dissertation takes a different road to incorporate active learning interventions using unique materials in two undergraduate engineering classes. In mechanics of materials, 3D printed multi-material parts combined with an acrylic apparatus and group activities were used to engage the students in four specific topics. In geometric dimensioning and tolerancing, a machined part and hands-on inspection tools were used to in a similar manner as the mechanics of materials interventions. This research focuses on not only the assessment of individual student and group performance, but also on incorporating student self-reported feedback to help weigh the advantages and disadvantages of developing and implementing the engineering interventions. This research also emphasizes the importance of including student feedback into the design of educational activities. The overarching motivating question of this research is:

What impact does incorporating active learning interventions in core mechanical engineering topics have on the learning experience and outcomes of the undergraduate students?

CHAPTER 2. BACKGROUND

Traditional methods of teaching have been recently challenged in an attempt to achieve more effective learning environments. In undergraduate engineering education, the methods used to disseminate information have changed little over the past half century [1]. Traditional methods, such as passive instruction or "chalk and talk", need reform due to their lower effectiveness in cultivating high quality learning for all students. A student's attention span during a traditional lecture decreases drastically over time, which results in a loss of retention of concepts [2, 3]. There is a plethora of evidence that has shown that engaging students through the promotion of student interactions and cognitive engagement leads to successful outcomes for students in undergraduate STEM (science, technology, engineering, and math) courses. It has been shown that the main way to approach increasing students' attention span is to incorporate active learning into the course curriculum [4, 5]. Research has shown that active learning strategies can increase course effectiveness beyond the results obtained with traditional methods [5, 6]. In a traditional lecture, professors have started to turn towards active learning to help improve students' knowledge retention during lectures [7]. Ruhl et al. asked their students to write down all of the facts that they could recall at the end of a typical 45-minute lecture [7]. Their research resulted in the students who participated in this exercise recited more correct facts throughout the semester than the control group. Research has been conducted in computer science classrooms on the student perception of peer learning activities and hands-on active learning activities compared to traditional lectures. The students indicated their preference for the active learning activities over traditional lectures and how the activities helped with their learning, problem formulation, and confidence [8].

Developing active learning interventions that improve knowledge transfer and retention is the focus of this dissertation. This literature review examines the space of active learning, it's impact on engineering students, and the importance of the development of active learning activities that foster knowledge retention.

2.1. Active Learning

Active learning in engineering education is a growing field due to the ongoing changes in implementation of best practices for students to obtain and retain information. In recent years, the pedagogical approach of active learning has become popular in STEM disciplines [5], such as mechanical engineering [9-11], physics [12], computer science [8], and biology [13, 14]. The form of active learning has taken place in STEM classrooms as flipped classrooms [8], peer learning [15], physical and virtual models [16], virtual simulations [17], and more. Active learning has been defined as "any instructional method that engages students in the learning process" [6]. Characteristics of active learning have been articulated by Bonwell and Eison as when students are "involved in more than listening", where more emphasis is on developing students' skills than the transmission of information [18]. This includes group learning, hands-on activities, and peer-to-peer instruction. Regardless of modes, the key is that active learning occurs when the brain is engaged in the intended information.

Active learning interventions have been gaining more traction regarding how they impact student learning, what types of activities can be done to improve engagement, and how the intervention can be optimized to enhance knowledge retention. Active learning is known to improve learning and depth of understanding of simple or complex subjects, while simultaneously improving performance in STEM courses [6, 12, 19, 20]. In the K-8 space, "...authors in the cognitive science discipline suggest that classrooms with an active learning approach can increase student motivation, knowledge retention, and content transferability", according to Cattaneo [21] (pg. 144). Active learning incorporated into STEM classes improves in academic achievement, decreases failure rates, and closes the achievement gap by raining the achievements of marginalized or disadvantaged groups [5, 6, 12, 13]. Active learning is continuously implemented in technology courses as a beneficial approach to teaching and learning in engineering, specifically mechanical engineering [10, 22].

2.1.1. Types of Active Learning

Active learning – as it pertains to engineering – has been referred to in literature as taking on three other common forms: Collaborative learning, Cooperative learning, and Problem-based learning (PBL) [6]. Collaborative learning is viewed as an instructional learning style in which students work together in groups, versus the typical individualized learning [23, 24]. Collaborative and cooperative learning are often thought of in the same way; cooperative learning involves students working in groups to strive towards common goals, while being assessed in an individual manner [24]. Problem-based learning is an instructional method that introduces specific problems relevant to the course material at the beginning of the lesson to be used as context for the concept(s) to follow [6], or developing problem solving skills with proper support from the instructors [21]. In this research, the combination of cooperative learning – through group learning – and problem-based learning – through active learning modules – and its impacts on students in mechanical engineering is explored. Cooperative learning will be referred to as group learning in the following sections.

2.1.1.1. Problem-Based Learning

Problem-based learning is an active learning methodology that has become immensely popular as an educational intervention since its establishment at McMaster University in Canada by Don Woods [25]. As a pioneer in the field, Woods coined problem-based learning by utilizing the pedagogy in a Chemistry class for medical school, and students exceled due to this novel innovation to learning in which the problem drove the learning. [26]. The main benefit of problem-based learning is the ability for students to have an application or workplace-based experience in the classroom instead of memorizing and repeating knowledge. A challenge of problem-based learning is the willingness (or lack thereof) of students to participate in active learning modules [1, 27, 28].

In addition, the adaptation of problem-based learning has translated to the engineering field [29-31]. This method has been seen as an effective approach to linking the material being taught in engineering to real-world problems that students will encounter after graduation [29]. Researchers determined that problem-based learning sets students up for immediate academic success in engineering classrooms and the pre-requisite courses for mechanical engineering students. Nizaruddin et al. [29] used problem-based learning in calculus for mechanical engineering students. The researchers facilitated cooperative learning with 28 students and traditional learning with 28 other students. As expected, the achievement of the students using the problem-based learning condition were far beyond the achievement performance of the students subjected to traditional learning styles. Similarly, Arsani et al. [31] used problem-based learning in a chemistry class within the mechanical engineering department at Bali State Polytechnic and used a control group to understand the impact of PBL versus traditional classrooms. The distinct difference is the application of multiple representations to account for learning styles (verbal and visual learning) in their active learning activities. This research highlighted the advantage of the professor as the facilitator and motivator to help the students develop deep-thinking skills. The outcome was similar to that of Nizaruddin; the students exposed to the alternative active learning method achieved better learning outcomes than the control.

2.1.1.2. Hands-On Learning

Hands-on learning is a particular type of active learning. Hands-on activities tend to have one or more items for students to observe and interact with, as they learn about the intended topic. Students are given objects to look at and manipulate, thereby leveraging several senses to focus cognitive attention on sensory inputs to increase learning. Further, the act of manipulating physical objects will facilitate an instructor's ability to prompt students to engage effectively in active learning. In some cases, students will create the 3D objects themselves, which will further increase the cognitive engagement of students. Learning is likely to improve when students are given the opportunity to engage with the materials through a variety of channels of input (e.g. sight, touch, hearing), provided the cognitive load of the multiple inputs is appropriately managed [32]. Even though hands-on learning has been pushed in the past as a way to promote better learning outcomes in students, Schwichow et al. suggests that it does not matter if the activity is physical or virtual, cognitive processes are occurring in some form [33].

2.1.1.3. Group Learning in Engineering

Group learning in engineering is an active learning approach that is utilized all throughout the curriculum, especially within senior capstone design courses. The group learning environments in engineering and technology are ones in which students work in groups on different virtual platforms [34] or in person [22, 35-37]. The widely known advantages of group learning are that it promotes engagement, diversity of team members and creativity, and has shown positive impact on students' knowledge retention and attitudes towards learning [37]. The widely known disadvantages are the willingness of students to participate and share knowledge, the lack of reliable assessment techniques for individual contributions, the social and discursive dynamics of a team [36], and the diversity of the group abilities and backgrounds [37]. The last aspect of the disadvantages, the diversity of abilities and backgrounds, can also be considered an advantage with peer collaboration, especially with the Jigsaw method [35]. In group learning, the Jigsaw method is employed by teaching students certain concepts in their designated groups, and then assigning them to their project groups to help disseminate that information to their group members. This method helps establish the role of students and promotes collaboration, peer-to-peer learning, and knowledge transfer [35].

These group or collaborative learning environments have been shown to improve the academic achievement of undergraduate engineering students due to the peer-supported cooperative inquiry to which the students are exposed [22, 38]. Small group collaboration was studied in a revised course program, called SCALE-UP, and promoted student centered learning in statics and dynamics – two introductory engineering classes. Even though some of the advanced, better than average students were frustrated with their less-knowledgeable groupmates, the learning activities that enabled social interaction and student engagement for mastery of the material was beneficial. This group collaborative environment based course resulted in increased indicators of conceptual measures in statics and reduction of failure rate of the integrated statics/dynamics course [22].

2.1.2. Student Engagement and Active Learning

Regardless of the type of activity introduced in the classroom, the engagement of students should be of high priority. Astin believes involvement in such activities is an important predictor of a student's success in higher education [39]. Well-thought of activities promoting engagement of students during learning are not foreign to STEM classrooms [5, 40].

Student engagement has held a multitude of definitions in the literature throughout the years. Student engagement, as it pertains to this dissertation, is defined by the Glossary of Education Reform as the "the degree of attention, curiosity, interest, optimism, and passion that student show when they are learning or being taught" [41]. Barkley explains student engagement as the phenomenon that occurs when motivated students are given opportunities for active learning [42]. Axelson and Flick believe it is possible that student engagement may be the "byproduct of the learning environment that suits the students" [43]. This dissertation emphasizes engagement as a result of projects that appeal to and stimulate the intellectual curiosity of the students through active problem solving. The curiosity of the student is thought to increase the engagement of the students throughout the problem-solving active learning process proposed in this dissertation [41].

2.1.2.1. Improving Student Engagement

Zepke and Leach proposed actions for the enhancement of student engagement in the classroom [44]. One action focuses on enhancing the students' self-belief, which is a key attribute in motivation. Although Krause believes there is no distinct factor identified that helps motivate learners to engage, they state students tend to be their own learning agents due to constructing their own knowledge [45]. Llorens et al. asserts that students' self-efficacy and engagement grew when they believed they had the necessary resources to achieve a task or goal [46].

Motivation for student learning and engagement has been examined by Ambrose as it pertains to the impact of value and expectancy on learning and performance. Ambrose explains the more students value a goal and expect success in attaining the goal, the greater their motivation will be to pursue it [47]. Value, particularly in terms of goals, is a key feature of motivation influence. When one accomplishes a goal or task, they gain satisfaction and therefore that experience they went through is deemed valuable. For expectancy, efficacy expectancies are essential for motivation and engagement [48]. An example of efficacy expectancy is the belief that one is able to do the work for not just a grade, but they are capable of doing the work to make the grade [48]. In this work, the combination of value and expectancy have been introduced through frequent active learning modules with similar structure.

One strategy that was proposed to address the combination of value and expectancy was to give the students the opportunity to reflect on their assignments [47]. In this work, the students were asked to reflect via surveys. These surveys asked how valuable the students believed certain portions of the project were and their opinion on what they expected from the modules in the future.

Another action is recognizing that instructors and teaching quality are central to the engagement of students; for example, the instructor is providing deep learning experiences [49], a supportive learning environment visible to the students [50], or the instructor seems approachable and supportive [14, 51]. Another proposed action is to create learning that is active, collaborative, and fosters learning relationships. Active learning in groups plus a student's outside of class peer interactions and social skills are important in engaging students [44]. Moran and Gonyea revealed that peer interaction supported students' engagement and outcomes [15]. These interactions with peers can lead to social skill and higher scores on course assessments.

2.1.2.2. <u>Student Resistance to Active Learning Activities</u>

Despite the push to help students learn in a more engaging fashion and promising research that favors the results of the efforts, there are students who do not enjoy alternative methods of teaching [28]. Some students are in classes to learn enough to pass and move to the next stage in their undergraduate or graduate career, and therefore they do not see the benefit of non-traditional classrooms. Consequently, the students may not perform as well as those who see the beneficial nature of active learning in the classroom and try their best to absorb the information.

Unfortunately, there hasn't been much research focused on how to help the students who are hesitant or resistant to the active learning approach in STEM undergraduate classrooms. Tharayil et al. have developed explanation and facilitation strategies to help combat the student resistance to active learning [27], which can be used as a starting point for instructors.

2.2. Active Learning in Mechanical Engineering

Over time, the interest in the relationship between concept visualization techniques and student performance has increased. For some engineering concepts, students lack the ability to grasp the intricate portions of the concepts [1] and how they connect to the physical world. With the advancement of technology and the internet, there have been various methods to help students visualize and grasp concepts through three-dimensional (3D) technology, ranging from Virtual Learning Environments [17, 52] to 3D printing [20, 53, 54].

2.2.1. Engagement through 3D printing

Using 3D technology to assist in classrooms has become a popular, innovative tool to increase a student's academic performance when utilized for class content [54]. 3D printing has been used in engineering classes as a way to develop physical prototypes from students' ideas and modeling efforts. Visualization through 3D printing for prototyping has been shown to have a tremendous impact on the engagement and performance of students when they see their work come to fruition [54]. Through class projects, students become excited, and anxious for more, while tying in the engineering theory of the projects.

The main engagement factor comes from the students producing 3D printed parts, but 3D printing has also been used to produce artifacts to aid in learning different concepts in engineering and beyond [20].

2.2.2. Hands-On Learning in Engineering

In mechanical engineering, there are countless subjects in which a hands-on active learning approach to interventions can be especially helpful to students for a more engaging, memorable experience in the classroom. The active learning approach has been incorporated into traditional lecture in classrooms using everyday objects [10], lab projects [55], computer-based tutorials [56], and other non-traditional lecture activities [11, 57]. The goal of these interventions is to increase student performance in various topics in order to demonstrate subject comprehension and retention. These interventions have resulted in various positive impacts on student learning and engagement.

Hands-on learning in statics has been examined by Coller [57] and Lesko et al. [11]. Both took a comparable approach in an engineering mechanics - statics course. Lesko et al. performed a study at Virginia Tech, and Coller ran the study at University of Illinois. An introductory engineering mechanics class received hands-on manipulatives for different topics in the curriculum, such as vector decomposition, friction, and two-force bodies. The studies were conducted by giving half of the students the hands-on activities and the other hands-off activities – the more traditional class activities. Both studies resulted in a lack of significant differences in the examination scores throughout the courses [11, 57]. Although Coller found this lack of notable difference, they concluded that the electrical engineering students' scores showed that they may have benefitted more from the activities than the mechanical engineering students [57].

Mobile, hands-on learning has been explored in the mechanical engineering courses focused on strengths of materials, dynamics, and vibrations. These mobile experimental platforms have been studied to create minimal-material, lab set ups that can be transferred from tabletop to tabletop [58-61]. Ferri et al. developed with a beam bending apparatus to help illustrate and analyze the concepts of stress and strain on the beam [59-61]. This beam bending apparatus was versatile and able to show multiple types of beams being stress tested, plus extract data from the experiment where the students could see the linear regression of the applied load. These experiments had in impact on many of the knowledge topics the students were tested on [59].

Ferri et al., also developed mobile single degree and two degrees of freedom experiments to potentially incorporate in-person laboratory structures [58, 60]. One was for kinematic structures to help student visualize how mechanisms move. Another was for vibration and dynamics experiments. These portable apparatuses were intended to be used to help students understand the topics of vibrations and dynamics from the lab setting and hopefully move to the home setting [58].

Linsey et al. used active learning interventions in mechanics of materials and disseminated the activities within three different institutions to understand the effectiveness of the activities [10, 40]. The activities included interventions to enhance understanding of failure modes, combined loading, and stress differentiation using everyday objects, such as tootsie tolls and foam rods. The interventions were incorporated in topic specific lectures.

The result of the intervention showed that the active learning products increased student learning compared to traditional lecture [10].

2.2.3. Virtual Active Learning

In addition to expanding the in-class learning possibilities, 3D printed model and corresponding apparatuses can be deployed in virtual learning environments when combined with web-based video learning. With a growing number of programs being offered in online settings and the lessons learned from a year of primarily remote education in 2020, incorporating 3D-based teaching technologies can be useful in the future of engineering education. In this area, studies present ways of integrating 3D technology with Virtual Reality (3D) to enhance learning by accessing multimedia content [62], understanding and visualizing content [63], and facilitating the virtual learning process [64].

2.3. Active Learning in Manufacturing and GD&T

Geometric Dimensioning and Tolerancing (GD&T) is a topic that is used in design and manufacturing for machinery, equipment, and other important devices in the world. Part specifications are important to engineering designers because products need to be designed for certain functions and design intent. GD&T can be called a language in which designers and machinists communicate to reach the goal of delivering an acceptable part. In undergraduate curricula, many students are not taught the breadth of information associated with GD&T. Since it is a specific topic, typically included in a manufacturing or design class, there have been limited studies that have focused strictly on GD&T [9, 55, 56, 65, 66].

GD&T basics, such as understanding tolerances and symbol meanings, has been introduced through simple hands-on experimental acrylic models to an introductory design class at Georgia Tech to help students visualize the concepts when learning a basic overview [67]. Because it is heavily tied to manufacturing, the concepts are often taught in manufacturing courses in colleges. Yip-Hoi, at Western Washington University, took a design for manufacturing approach in teaching students GD&T by allowing them to only design the part, but their manufacturing processes were also based on annotated GD&T drawings they developed [56]. GD&T instruction was used in a design graphics course at Southwest Texas State University, where students were explained GD&T in three parts to help them understand why it's used and how the inspection occurs on a Coordinate Measuring Machine (CMM) [66]. At University of Texas, Dallas, concepts, such as tolerance zones, datums, and material conditions (most/least material conditions - MMC/LMC), were illustrated through 3D computer models and 3D printed parts. These interventions resulted in benefits to students' learning from the 3D technology [16].

Although the concepts have been taught to students as activities embedded in other curricula, Illinois State University offered TEC333 - Geometric Dimensioning & Tolerancing in Fall 2015 as a stand-alone course [9, 55]. Branoff, a TEC333 instructor at Illinois State University, used Fall 2016 and Fall 2017 to study how the course structure impacted the students' learning though pre-test, weekly quizzes, exams, and lab activities. Branoff found that there was a benefit to evaluating all of the data collected because it gave a comprehensive understanding of concepts the students did not grasp well throughout the course and what to focus on in future semesters of TEC333 courses [55]. The data resulted in the students improving on some topics in GD&T, but there were always some topics that he believed he needed to pay more attention to when teaching in subsequent semesters.

2.4. Evolution of Engineering Instructional Approaches

Engineering education literature calls for expanding the approach to instructional methods in response to the evolving nature of engineering practice, design, and emerging technologies. Identifying the five major shifts in engineering education, Froyd, Wankat [68] note the shift away from "hands-on practice to mathematical modeling and scientific analyses." Further, the authors note that while new technologies were expected to transform education practice and outcomes, significant changes have not yet been realized. Examining the role of information, communications and computation technology (ICCT) in the context of engineering education, Koretsky and Magana [69] identify the importance of aligning technology with instructional practice. Using a Delphi approach, the authors recognize the importance of instructors' beliefs, their knowledge, and organizational support in ensuring that university administration and faculty development programs equip faculty with the knowledge and skills to integrate computer technologies in their instructional approaches.

2.4.1. Deploying and Leveraging Tools to Improve Engineering Education

In recent years, scholarship focusing on the role of incorporating new technology in classroom instruction has highlighted the need for adopting an integrated and adaptive approach to incorporate active learning approaches with consistent instructional support to maintain student engagement and foster a productive learning environment [70]. Innovative approaches to instruction have been deployed broadly in foundational engineering courses [54], electrical engineering [70], design thinking and mechanical engineering [71, 72]. Sorby [73] presents the results of a long-term program aimed at developing 3D spatial skills with a special focus on women in engineering. Although these researchers were able to incorporate the innovative tools into their classrooms, there has been unfortunate pushback from some instructors tasked with designing and implementing modules into their teachings. The main problem with these innovative activities is that instructional reform has to be wanted by the class instructor and time needs to be allocated - not forced on them [28].

Several active, interactive, and tactile learning approaches have been incorporated in mechanical engineering curricula. These include simulation-based learning in a machining technology course [74], and long-term multi-semester benchtop hybrids across multiple courses [72]. The results of such interventions have been positive to mixed, with improvements in students' thinking and design approaches but limited effects on retention.

2.4.2. Pedogeological Approaches and Intervention Design

Development of interventions that are thought to make an impact on the knowledge retention and performance of students in classes have one thing in common: they are developed. Pedagogical design has been studied in various fields to help efficiently impact the desired educational outcomes for certain curricula [75-79]. Although, pedagogical approaches to whole curriculum designs have been studied, there is less literature about the design of supplemental in-class educational interventions.

Outcome based education (OBE) refers to an approach in which, through teaching and implementation, students reach the final learning results set forth [80]. Outcome based learning focuses on highlighting the learning outcomes, why the outcomes are desired, effectively helping students achieve the outcomes, and developing metrics to measure whether students achieved the final result (or maximum ability of the student at that stage of learning). OBE has been adopted through different techniques, such as modular education, to help implement better practices in classrooms. Modular education is a way to help students master concepts in class through independent learning rather than through traditional lecture. Development of learning modules has many elements to consider. The learning objectives, expected outcomes, equipment, and other elements have a distinct impact on the success of the modules when implemented in classrooms [78]. Modules are different in size and content, but the objective is the same – to help students develop a deeper knowledge. Omonvich outlined four steps in the module preparation process: (1) methodological analysis of material students are to learn; (2) setting goals and shaping planned learning outcomes; (3) designing activities based on the capabilities of students; and (4) experimental verification. Using these steps to develop learning material has shown that creating a learning module requires ongoing research and for the instructors to have pedagogical experience [78]. This will decrease the likelihood of material being omitted, insufficient, or unorganized so that students will be able to reach their desired outcomes.

2.4.3. Sequencing Theory and Practice

Another critical question to answer in the process of module design is the timing at which hands-on learning modules are presented and delivered to students. Natarajan et al [77] present an approach for testing the order in which theory and practice are delivered in an engineering course, along with an end-to-end demonstration of the steps. Using Cohen's, the authors conclude that the "Practice before theory" approach has a slightly higher difference in the pre- and post-test scores. More importantly, the authors indicate the importance of incorporating student feedback when measuring the effectiveness of any interventions.

Along with the development, gathering feedback through the form of assessment is crucial. Teaching and learning must be interactive, and instructors should know about the progress and difficulties their students have. This knowledge should lead to adaptation of the teacher's work to meet the students' needs [81]. This is critical to the development of interventions because of the repetitive cycle instructors may go through to refine their intervention to enhance student participation, engagement, and performance [81].

2.4.4. Gaps in the Literature

To summarize, there is a vast and growing literature on active learning and intervention design for engineering students. Most instructional design studies focus on summative evaluations, relying primarily on student data gathered either through surveys or student performance. Most studies, however, stop short of providing insights into the intervention design and implementation process.

Regarding student outcomes, for decades, students are given formative and summative assessments as an indicator of comprehension and understanding. The instructor uses these as a baseline to assess their knowledge of the current subject matter and identify what the topics students may have missed. Typically, instructors give their students feedback on how they are progressing and are not receptive to students voicing their opinion on their teaching style. In fact, most studies focus on the importance of giving students feedback [82, 83] or peer-to-peer [84] feedback after class assessments and projects. The literature does not examine the space of the instructor centering their progression of the topic or method of teaching based on the qualitative response of the students – this is just as important. This dissertation leverages the importance of implementing student feedback and enhancing the activities they will be using to obtain knowledge.

Mechanics of materials is a relevant field in all mechanical engineering curricula. There have been studies for active learning in this space [10, 40] focused on utilizing different activity methods for individual topics in the classroom. Research in the mechanics of materials active learning space lacks sequence and consistency throughout the duration of the semester. Supplemental activities to traditional lectures have been incorporated into classrooms, resulting in the researcher justifying the impact the activities made on the students. Yet, continuous implementation of these supplemental activities into a mechanics of materials classroom has not been examined. Incorporation of a consistent active learning framework for hard-to-visualize topics in a mechanics of materials class and the student outcomes of the activities is addressed in this dissertation.

Although a growing field, very few researchers have examined the role of coursework and activities in the GD&T field. The students have been exposed to GD&T and engineering drawing [85] primarily through courses supplied by manufacturing or mechanical engineering curricula at their university. The research has been focused on understanding what basic and advanced concepts the students absorb based during labs [9, 55], online coursework [85], and modeling activities [16]. Lin et al [86] decided to develop a class infusion project that would help where manufacturing and specification identification is not in the university curriculum. Although Lin et al. have a good framework for an infused traditional lecture on GD&T into a related class, the use of active learning methods for GD&T are limited. This dissertation discloses the impact that implementing GD&T interventions, centered around basic concepts and manual part inspection methods, has on the students.

This dissertation aims to address these gaps by laying out the process of developing in-class interventions. In a step-by-step approach, the process is laid out for selecting topics for designing interventions, composition of hands-on learning activities and the iterative process of incorporating and refining the intervention designs, based on student and implementer input. This dissertation focuses on the developmental stages of intervention design, the implementation of these developed modules, and the translation of the module design concepts to a different topic in mechanical engineering. First, the role of iterative adaptation of teaching materials in mechanics of materials is presented in response to revealed and stated responses of student participants and the role of exogenous shocks in designing engineering curriculum are addressed and examined. Secondly, the influence of the iterative adaptation of the teaching materials is examined throughout three semesters. Lastly, the implementation of these adapted modules into a GD&T classroom and its' impact on students' knowledgebase is examined.

The past year has presented higher education with numerous challenges, chief among them student engagement and participation and the challenges of remote learning [87-89]. As such, any interventions that require in-person engagement or active learning, especially using materials or apparatus were reconfigured and reevaluated to account for the new learning environment.

CHAPTER 3. THESIS STATEMENT

Active learning interventions in mechanical engineering curricula through iterative development and deployment leads to improvements in students' information absorption and their ability to complete knowledge-based tasks.

CHAPTER 4. DEVELOPMENT OF ACTIVE LEARNING MODULES

Tracking the development of a pedagogical approach is essential to helping future educators understand why certain learning interventions were created and how the feedback was funneled into the creation of the current approach. Educational interventions were deployed, and formative and summative assessments were used to understand what the students obtained from the intervention. This approach was employed to not only incorporate the assessments, but the feedback from the participants in the study, such that the intervention is as effective as possible. This includes understanding how students perceived the value of the intervention, learning preferences and responsiveness to differing types of instruction styles of the students, and how their self-efficacy was impacted after completing the interventions.

The development process of the active learning modules for mechanics of materials was important to decomposing the educational interventions in order to determine what would work or not work well in the classroom. Mechanics of materials was chosen as a topic to be examined because it is highly theoretical and often taught in the abstract, and there are concepts for which it may be beneficial to see them embodied in the physical world. These modules were created to break down and reinforce the knowledge of nine overarching topics in mechanics of materials. Nine modules were originally developed in the first iteration of design. With critical feedback, the modules were revamped in a second design iteration. Due to time constraints on classroom instruction throughout the semester, the second iteration of modules was reduced to cover only topics that students tend to have the most trouble with. These topics are: Axial Loading, Torsion, Combined Loading, and Beam Deflection.

There were multiple iterations that were done to develop the structure of the modules. The development of these modules led to group-based, step-by-step guides with instructor input that helps students complete more advanced exam and homework type problems. Class observations, focus groups, a pilot module deployment, and full-scale module deployments were conducted throughout the semesters. Feedback was obtained from the participants and external evaluators. The feedback from these studies was analyzed, translated into recommendations, and implemented to improve the modules. In the following sections, the development process is described to the arrival at final version of the modules.

In the first semester, Fall 2017, the project design team commenced in-person observations of three different sections of the Deformable Bodies course to understand how the instructors-of-record present and deliver the course material (Figure 1). The team also conducted focus group discussions to gauge students' response to the material and the module implementation timeline for the classroom. In Spring 2018, a module pilot was deployed to observe the flow of the intervention implementation. The next school year was then used to develop modules for the necessary topics and prepare for deployment. In Fall 2019, Spring 2020 and Fall 2020, the modules were deployed and refined over the semesters. In Fall 2020, the modules were adapted for and deployed virtually, due to the COVID-19 pandemic. These intervention structures will be explained further in the following sections.

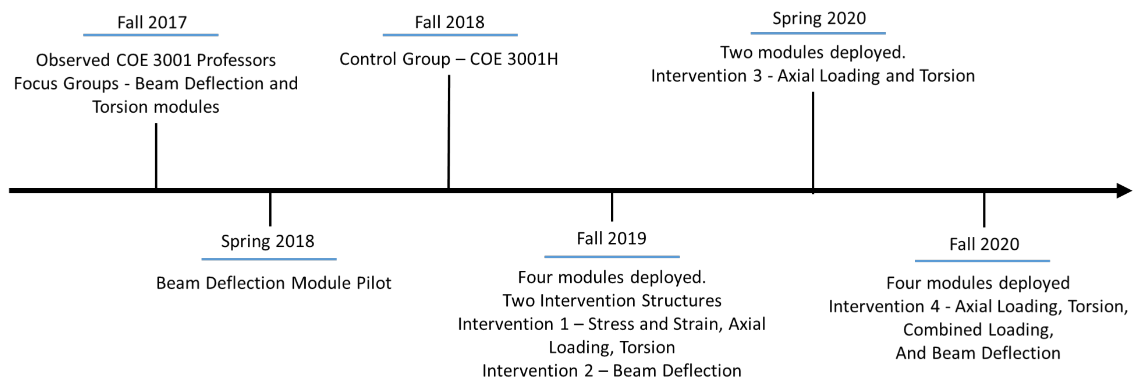


Figure 1: Intervention design and deployment timeline

4.1. Mechanics of Materials Module Topics

The modules were created to be deployed as interventions in 75-minute, COE 3001 Deformable Bodies classes at Georgia Institute of Technology. Deformable bodies courses, also known as mechanics of materials, teach engineers the fundamentals of how to design any type of structure to be safe, whether that structure is a bridge, a submarine, an antenna, or even a chair. The built environment, which many people take for granted as safe and well designed, hinges upon the engineers' understanding of mechanics of materials to ensure reliable, resilient, and robust design. Currently, most core undergraduate curricula teach mechanics of materials in a highly theoretical manner, mostly using paper textbooks, which include textual definitions and descriptions of key concepts, with illustrations to communicate material behavior in given cases.

The module topic areas were selected based on the fundamental concepts covered in COE3001. In order to understand the COE3001 course and how it is taught in at Georgia Institute of Technology, researchers observed and recorded observations of the teaching styles of multiple professors and the students' behaviors during each of the observed lectures. Originally, nine topics fundamental to mechanics of materials were selected and deemed important to develop modules for students to succeed. Although some topics have a breadth of information that needs to be absorbed, targeted learning objectives were based on the content the students get repeatedly exposed to. Following the module selection, instructor feedback, and time needed per module deployment led to a decision that this list of nine should be reduced to four topics. The four topics ultimately selected for interventions include: Axial Loading, Torsion, Combined Loading, and Beam Deflection. The original nine topics are shown in Table 1. The highlighted topics and descriptions are the four topics that are were focused on. Learning objectives were first developed for each module topic. These learning objectives were based on the syllabus and course content of the instructor-of-record in each of these topics.

Table 1: Nine Core Topics of Mechanics of Materials (Blue highlighted are the Four Current Module Topics)

Topic	Description
Stress and Strain	Overall basics stress and strain
Axial Loading	Impact of axial loading on the shape and deformation of various bars
Torsion	Impact of torsion on the shape and deformation of various bars and shafts
Shear and Moment	Understanding how to plot and calculate the shear force and moments throughout a beam
Stresses in Beams	Understanding different types of stresses present in a member
Mohr’s Circle	Using a method to calculate plane and principal strain and stress values in a stress element
Combined Loading	Impact of a mixture of forces on the shape, deformation, and stresses in a member
Beam Deflection	Impact of transverse loads on the shape, deformation, shear, and moment in a beam.
Column Buckling	Impact on the behavior of a column in compression subjected to an axial load

Table 2: Module Title and Learning Objectives. Bolded topics represent the topics that were deployed using the Intervention 3 structure

Topic	Learning Objectives
Stress and Strain	• Explain the stress-strain relationship for various cross sections of structures • Analyze the behavior of a structure when experiencing normal stresses and shear stresses • Create a free body diagram for an object under loading • Apply the concepts of stress and strain to real world examples
Axial Loading	• Predict how axial forces applied will impact the structure with varying loads • Calculate force and displacements to analyze the stresses in the structures • Create free body diagrams and axial force diagrams describing the loading conditions on the bar
Torsion	• Predict how bars of different sizes react under different types of torsion • Create free body diagrams describing the loading conditions on a bar • Accurately calculate reaction torques, shear stress, shear strain, and angle of twist
Combined Loading	• Predict the impact of the combination of more than one type of load on a structure • Create free body diagram describing the loading conditions on the structure • Analyze stresses in the structure at points of interest due to the applied loads • Develop stress matrix due to the stress resultants calculated
Beam Deflection	• Predict how beams deflect under various loads • Accurately calculate reaction forces and moments • Apply the concept of superposition to beams under loads

Stress and Strain was deployed during the first intervention deployments before the ultimate decision was made to reduce the number of modules. Stress and Strain was not included in the subsequent deployments when the decision was made due to the amount of time the module deployments took from the regular class time. In theory, if nine topic-specific modules are deployed throughout the semester, that's nine classes less the instructor-of-record has for other planned lectures and deliverables. After careful thought, Stress and Strain was not one of the top topics that the instructor-of-record and implementation team believed would serve the students the best. In the future deployments, the Combined Loading module was identified as one of these more beneficial topics in mechanics of materials. The five topics, descriptions, and learning objectives are presented in Table 2.

4.2. Iterative Module Development and Implementation

As noted earlier, the design and implementation team followed an iterative, incremental, and adaptive approach to designing active learning interventions in mechanical engineering classrooms. To achieve this goal, the implementation and evaluation teams collected student performance metrics and feedback as part of each module deployment exercise. The information from the metrics, feedback and student self-reports was then used to iteratively evaluate and redevelop the modules throughout the semesters deployed.

There were multiple iterations that were done to transform the structure of the modules. The development of these modules led to group-based, step-by-step guides that help students complete advanced exam and homework type problems. Class observations, focus groups, a pilot module deployment, and full-scale module deployments were conducted throughout the semesters. Feedback was obtained from the participants and external evaluators. The feedback from these studies was analyzed, translated into recommendations, and implemented to improve the modules. In the following sections, the development process is described to the arrive at final version of the modules.

Table 3: Breakdown of components of each Intervention structure

		Intervention 1	Intervention 2	Intervention 3	Intervention 4
Pre-Assessment	Knowledge Assessment	✓	✓		
	Self-Efficacy Survey			✓	✓
Module	Activity 1	✓	✓	✓	
	Activity 2	✓	✓	✓	✓
	Activity 3	✓			
Post-Assessment	Knowledge Assessment	✓	✓		
	Self-Efficacy Survey			✓	✓

Each module structure iteration is called an Intervention. Each iteration that led to a significant alteration or removal of a portion of the module structure incremented the Intervention number. Table 3 breaks down the included components of each Intervention. Intervention 1 included a pre-assessment, three group activities (Activity 1, Activity 2, and Activity 3), and a post-assessment. In this intervention, unlike the others, Activity 3 was included. Activity 3 emphasized real-world applications of the module topic, which is described in later sections. Intervention 1 turned into Intervention 2 when Activity 1 and Activity 2 were altered, and Activity 3 was removed in response to student feedback and classroom observations. Intervention 2 turned into the current in-person module structure, Intervention 3, when the pre- and post-assessments were removed to incorporate more time for the two group-interaction activities. Intervention 3 included a pre-assessment, two group activities (Activity 1 and Activity 2), and post-assessment. This structure has been developed based on the feedback obtained throughout the duration of the project. This feedback will be explained in later sections. Intervention 3 evolved to become Intervention 4, due to the need for virtual adaptation of the module during the COVID-19 pandemic. The virtual adaptation prompted the removal of Activity 1 and change in the method that students utilized the 3D model for Activity 2. Instead of the in-person manipulation of the 3D model, Intervention 4 included a video that showed a range of views of the impacted structure that could be viewed if the students applied the loads in-person. The in-person Intervention 3 and the virtual adaptation Intervention 4 structure will be explained in this dissertation.

4.2.1. Intervention Development and Deployments

Multiple iterations, combined with participant and external evaluator feedback were used to design the interventions. Class observations, focus groups, a pilot module deployment, and full-scale module deployments conducted throughout the semesters further helped refine the intervention design. The final design includes group-based, step-by-step guides that help students complete more advanced exam and homework style problems. The feedback from Fall 2019, Spring 2020, and Fall 2020 semester deployments was analyzed, translated into recommendations, and implemented to improve the modules in the following semesters, thus allowing an iterative approach to refining and improving the module deployment. The remainder of this section presents every step taken to refine the modules and the results of the changes.

4.2.2. Class Observations

Classroom observations were conducted to help gain exposure to the operation and instructional aspects of the COE3001 class at Georgia Tech. During the observations, the research team studied multiple instructors' classroom environment, instructors' approaches, their choice and use of classroom technology, level of student engagement, and modes of class participation. The classroom observations also provided an opportunity to study the demographic makeup of a typical classroom, student behavior, and instructor responsiveness to the students' expressed and revealed requirements.

4.2.3. Piloting with Focus Groups

Focus groups were conducted in Fall 2017 with compensated mechanical engineering student volunteers at Georgia Tech who had no exposure to the topic of mechanics of materials previously. The objective of the focus groups was to pilot the modules with students in groups and obtain qualitative feedback about the flow, engagement level, and effectiveness of the content of the module. Focus group pilots were performed for the Torsion and Beam Deflection modules. These topics were piloted because they are theoretical but had the ability to incorporate the 3D-printed multi-material model into the activities. There were eight participants total in the focus group pilots: four for Torsion and four for Beam Deflection. Two focus groups were run for each topic.

The modules piloted in the focus groups had the following structure, called Intervention 1, as depicted in Figure 2: five-minute pre-assessment, Activity 1 – refresher topics on paper worksheets, Activity 2 – hands-on activity and problem solving, Activity 3 – real world examples, five-minute post-assessment. The assessments were five minutes each and were designed to measure the students' level of knowledge on the module topic before and after it was experienced. Activity 1 was used to refresh the students' knowledge on topics they should have learned from the course lecture content prior to deployment of the module. Activity 2 incorporated the 3D-printed model and apparatus into group work, to serve as a visual representation of the loading conditions that can be exerted and how they impact how the member (3D-printed model) behavior. Activity 3 introduced real-world examples to relate the concepts to every-day life scenarios and structures.

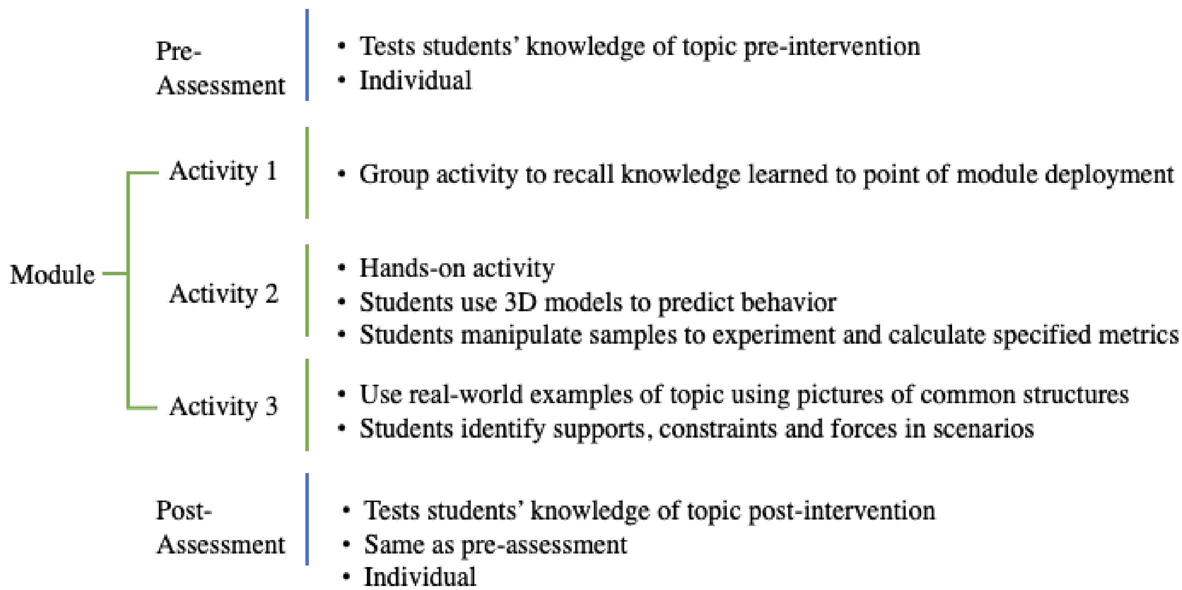


Figure 2: Intervention 1 structure

During the focus groups, the assessments were piloted to ensure they tested the knowledge covered in the modules. The focus groups also examined whether participants enjoyed working with the hands-on materials and if they deemed the activities useful to improving their knowledge of the topic. The data portion included the students having open discussions about the modules were conducted and recorded to gain an in-depth understanding on the perception and suggestions of the student volunteers. The students were, also, given a minute paper exercise where (student) participants were able to take a brief amount of time and write down their thoughts and responses to the focus group prompts. This minute paper exercise was incorporated into the focus group discussions to account for students who might be reluctant to share their thoughts in front of peers or disagree with the group during the open-talking session.

After analyzing the information from the focus groups, the feedback was used to refine the modules and further develop them for piloting in COE3001 lecture in Spring 2018. For all COE3001 deployments and control group data collection, the instructor-of-record remained the same.

4.2.4. Module Implementations

There were four semesters where the modules were implemented in the classroom: Spring 2018, Fall 2019, Spring 2020, and Fall 2020. In Fall 2018, the deployment was halted, therefore the deliverables were used as a control group to compare the other semesters.

4.2.4.1. <u>Spring 2018 COE3001 Pilot</u>

In Spring 2018, one module – beam deflection – was able to be deployed in the classroom with 32 students, in 14 teams of 2-3 students each. The module was structured as Intervention 1, with some changes to the content based on feedback from the focus group pilots. The COE3001 class was 75 minutes in length. This pilot was used to help understand if the timing was well designed for each section of the module, the flow of the module delivery, and how deploying the module before the content was covered in class would impact the success of the intervention. Through observation of this pilot deployment, it was discovered that timing could be improved, student engagement was fostered with the group activities, and the 3D model interaction needed some revamping. Timing in this deployment felt rushed towards the end of the class and more time could be allocated to Activity 2, less to Activity 3. This would have given the students more time to complete the post-assessment. Activity 2 needed to be revamped in a way that was less confusing for the students when understanding how to apply the loads, measure, and calculate specific stresses. After the observations were incorporated into the Intervention 1 format for the next iteration, the next step in the research plan was to collect baseline control data against which to compare full-scale deployment of all developed modules.

4.2.4.2. Fall 2018 COE3001 Control Group

A control group is necessary for this research in order to compare the outcomes of module participating students to a standard, lecture style class taught by the professor. The assignments were collected and graded digitally, and the exams were graded and scanned for analysis. These grades were collected to understand the level of students in the COE 3001 class, how they interpreted problems given throughout the course, and the strengths and weaknesses of the students' deliverables.

4.2.4.3. Fall 2019 COE3001 Deployment

In Fall 2019, eight modules were planned for deployment. The class consisted of 43 students and was 50-minutes in length. The length of the class for this semester was different than the original 75-minute class length because of how the professor was scheduled for Fall 2019. The Fall 2019 deployed modules were developed in the structure of Intervention 1. In the beginning of the semester, three modules were deployed: Stress and Strain, Axial Loading, and Torsion. Although there were plans for eight modules to be deployed, these module deployments were time demanding for the class schedule, and responses from the students were taken into consideration.

The feedback from the participants and evaluators was analyzed, and a new improved module design was developed for increased engagement and knowledge retention. In the initially deployed module design (Intervention 1), the problems given to the students were less advanced than those they would see in a homework problem or exam. The enhanced module design became Intervention 2; changes included removing Activity 3 – the real world examples, modifying the structure of Activity 1 to multiple choice, flash cards for the groups to solve and display, and altering the problem given to the students in Activity 2 to be a step-by-step guide to solving more advanced problems. In Intervention 2, Activity 2 was more guided by the research instructor, TA, and instructor-of-record than in Intervention 1. The last module deployed in Fall 2019 was Beam Deflection, and it was deployed with the Intervention 2 structure, outlined in Figure 3.

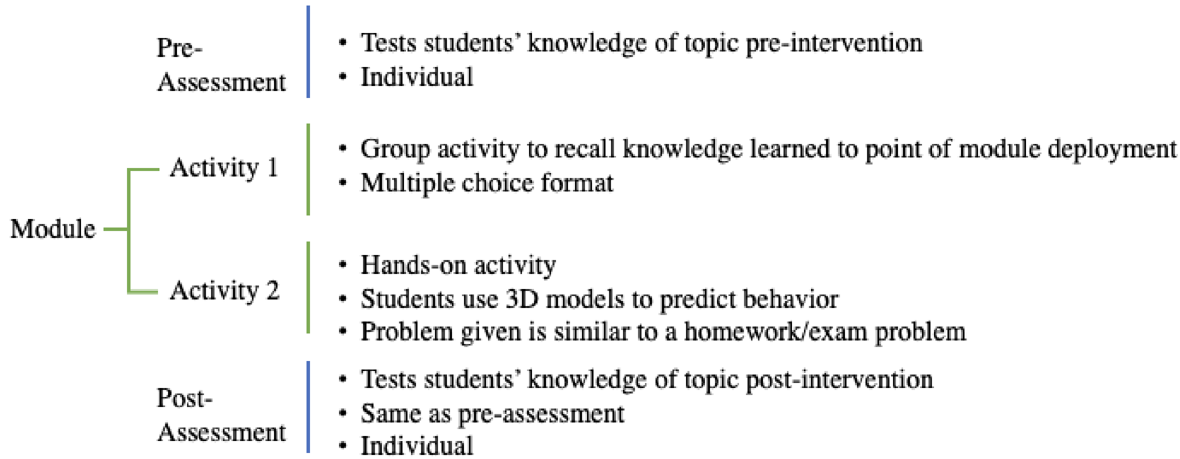


Figure 3: Intervention 2 structure

4.2.4.4. Spring 2020 COE3001 Deployment

After careful analysis of the feedback given by the evaluators and the students, the structure of the modules was improved once more for the Spring 2020 deployment. The COE 3001 class consisted of 48 students separated into 15 groups of 2-4 students. The new structure, Intervention 3 (Figure 4), was deployed in all modules in Spring 2020. One of the most noticeable changes is the removal of the pre- and post- Knowledge Assessment and implementing a Self-Efficacy survey. The changes came from careful considerations regarding the pre- and post- assessments. The feedback from the students indicated that the quiz-like assessment was frustrating. In particular, receiving the same questions in the pre- and post-assessments was the most frustrating part. It was determined that it would be more beneficial for students to report their abilities before and after the modules and use the formative (homework) and summative (exam) assessments to track their performance in the class, their knowledge retention, and problem-solving skill development.

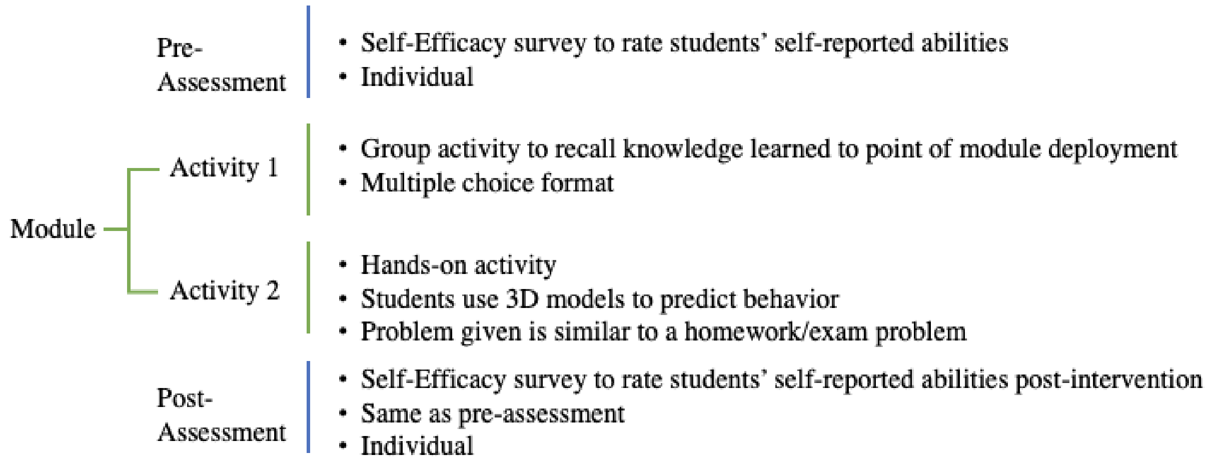


Figure 4: Intervention 3 structure

For the Intervention 3 structure, the plan was to deploy four modules: Axial Loading, Torsion, Combined Loading, and Beam Deflection. Due to the transition to virtual learning environments halfway through the Spring 2020 semester, only the Axial Loading and Torsion modules were able to be deployed, while the Combined Loading and Beam Deflection deployments had to be cancelled. Although this occurred, in this deployment, it was learned that Intervention 3 structure had an immediate, positive impact on students based on the feedback obtained.

4.2.4.5. Fall 2020 COE3001 Deployment

For Fall 2020, there was a full-scale deployment of the same four modules that were developed to be deployed in Spring 2020. The module topics stayed the same, but application of the module had to be changed. Amidst the pandemic, the modules for Fall 2020 were deployed virtually via BlueJeans. The modules were changed and adapted to be implemented virtually through videos and breakout sessions, which resulted in Intervention 4. In order to help the students visualize the 3D model in a way that was similar to the in-person implementations, videos were developed to include every perspective and every way a student could manipulate the model. For each module topic, the amount of manipulation of the part varied based on the number of forces that were needed for application. As for the module activities, the Axial loading module was implemented in the class with the two-activity structure. Due to time constraints and the BlueJeans capabilities, Activity 1 was nixed from the module. The online platform did not allow for the planned structure to be smoothly implemented. In the interest of the students' learning through an already tough virtual environment and class timing, Activity 2 was kept as the sole activity for remaining modules for the Fall 2020 semester.

4.3. Intervention Structure

The following sections present the components and activities of Intervention 3 and 4 in detail and summarize the changes from the previous iterations. In the beginning of each intervention deployment, each group of students were given a packet filled with all the physical and paper materials needed for the module. For Intervention 1, each packet consisted of a pre-assessment, the 3D model and apparatus for Activity 2 (Figure 4), and one module activity packet (Activity 1, Activity 2, and Activity 3) for each group member. For Interventions 2 and 3, each packet consisted of a pre-assessment, three numbered flashed cards for participating in Activity 1, the 3D model and apparatus for Activity 2 (Figure 4), and one module activity packet (Activity 1 and Activity 2) for each group member. The post-assessment was distributed after the students completed the activities. For Intervention 4, each student was given virtual access to a pre-assessment survey link, a packet for the module activity, and a YouTube video link for the 3D model manipulation video. The post-assessment was distributed after the students completed the activities.

Intervention 1 modules were deployed in the class immediately after the first lecture introducing the topic was taught by the professor. Feedback indicated that the students believed they did not have enough prior knowledge of the material to benefit from the module activities. They suggested they learn more about the topic before being introduced to the module materials and making the problems similar to their homework and exam questions for the module to be effective to them. Based on the feedback, the design team reevaluated the approach and the modules were deployed after all lectures of the chosen topic had been completed for the Intervention 2 structure and beyond (Figure 5).

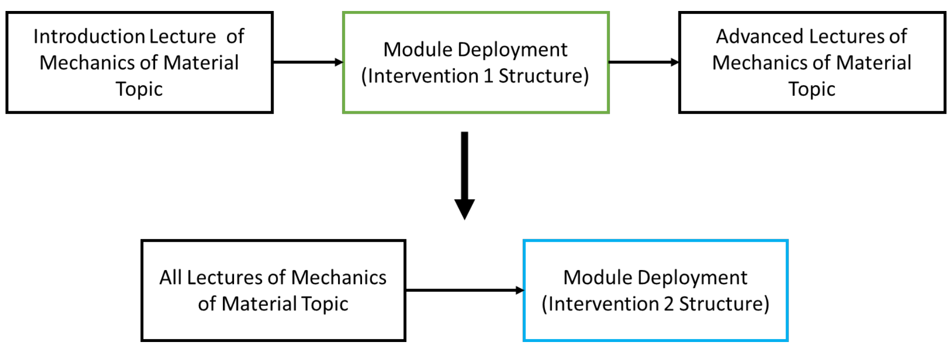


Figure 5: Initial (top) placement of module between lectures compared to the final (bottom) placement of module after all lecture topics were taught in Fall 2019. The final format was used for the subsequent semesters the module was deployed

Intervention 3 consisted of four crucial parts: Pre-Assessment, Module (Activity 1 and Activity 2), a 3D printed multi-material model and its complementing apparatus, and Post-Assessment. This structure was developed based on the feedback obtained throughout the duration of the project. Along with the Intervention 3 components, this section explains the premise of Activity 3 and why it was removed.

4.3.1. Pre-Assessment

Table 4: Outline of the Pre-Assessment Surveys

Module Deployment	**Pre-Assessment Surveys**
Axial Loading	Demographic Survey Learning and Instruction Survey Self-Efficacy for Axial Concepts
Torsion	Post Exam Survey for Axial Loading Module Self-Efficacy for Torsion Concepts
Combined Loading	Post Exam Survey for Torsion Module Self-Efficacy for Combined Loading Concepts
Beam Deflection	Self-Efficacy for Beam Deflection Concepts

The pre-assessment content varied based on the topic of the module that was being deployed (Table 4). The pre-assessment instruments consisted of survey instruments to measure personal learning and instruction styles, report self-efficacy, and to understand the impact of the module(s) previously deployed had on the homework. Learning and Instruction Survey was used to help understand what students preferred in an ideal classroom. The Self-Efficacy survey was used to understand the confidence students had in their knowledge of concepts and techniques necessary for completing the module. This survey established a baseline to compare to post-assessments to determine if the intervention had an impact on the students' self-reported abilities. The Post Exam Survey asked students how much they believed the module impacted their homework and exam scores. The time allotted for the pre-assessment portion was five minutes.

In Intervention 1 and Intervention 2, the pre-assessment consisted of a Knowledge Assessment, which was a quiz-like assessment to test the students current understanding of the module topic. This assessment was completed individually by each student. The Knowledge Assessment was the same for the pre- and post-assessment for these intervention deployments to have a one-to-one comparison of the students' understanding of the topic.

4.3.2. Module

After completing the pre-assessment individually, students worked in their pre-assigned small groups to complete two active learning activities - Activity 1 and Activity 2. The content of both activities was based on the homework and exam problems from previous semesters. The students were encouraged to collaborate with one another during these parts of the module to cultivate peer-to-peer learning, practice conceptual articulation, and discuss the reasoning behind problem-solving approaches.

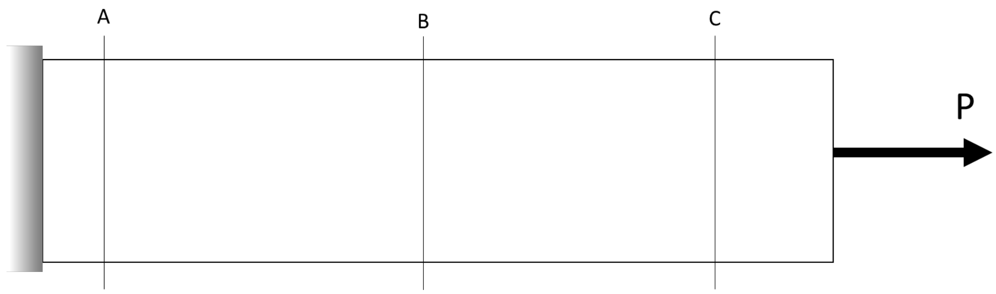
After working on Activities 1 and 2 in small groups, the instructor-of-record worked through the problems on the board to help the students check their answers and problem reasoning. This approach gave students a chance to formulate their thoughts about how to tackle a problem on their own – as they would during homework problems and exams. Once the module was complete, the answer key was added to their online course page, along with video links to solution explanations. In Intervention 4, the research instructor worked through the problems once the Activities were completed.

4.3.3. Activity 1

At the beginning of this study, in Intervention 1, Activity 1 was developed to be a "refresher" to the information the students would have learned in the lecture prior to the intervention and a bridge to the problems in Activity 2. This consisted of principles and concepts related to the specific module topic. For example, Activity 1 for the Axial Loading module emphasized the concept of Saint-Venant's principle, as shown in Figure 6. The activity was a quick, 10–15-minute part of the entire module. This was done in groups, but students were encouraged to fill out their own sections. In their feedback, students indicated that they did not only find not benefit from this Activity 1 Structure, they also were confused on how it would help them with more advanced problems. In response, the design team transformed Activity 1 into an active learning approach where students could work in groups.

Part 1: Understanding St. Venant's Principle

Draw an example of St. Venant's principle on the diagram supplied below. Assume the rectangular bar is fixed, with a length L, and subjected to a constant force P. Label the area with the highest stress by shading it in on the diagram below.



What do you think the stress distribution would look like at cross sections A, B and C on the diagram above? Draw in the designated spaces below.

Cross Section A	Cross Section B	Cross Section C

Figure 6: Example of Intervention 1's Activity 1 Structure for Axial loading

As a result, in Intervention 2 and Intervention 3, Activity 1's final form became an interactive, multiple choice style activity. It consisted of two basic problems with three answer choices each that could be solved in less than 5 minutes within the small groups. The students had three colored cards, labeled with their group number, that correspond to the choices given after the problems in the packet, as shown in Figure 7.

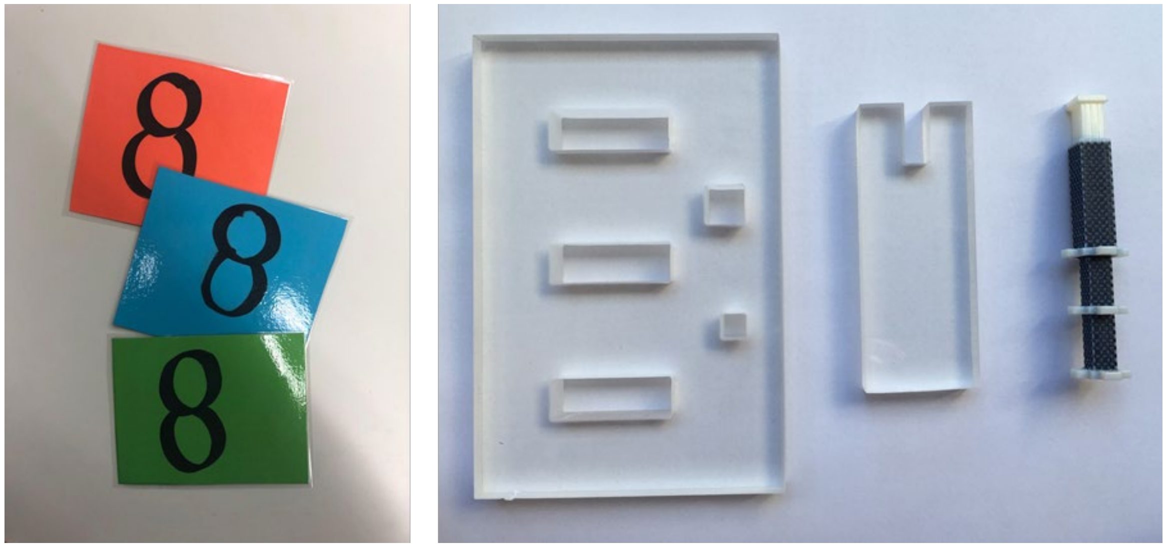
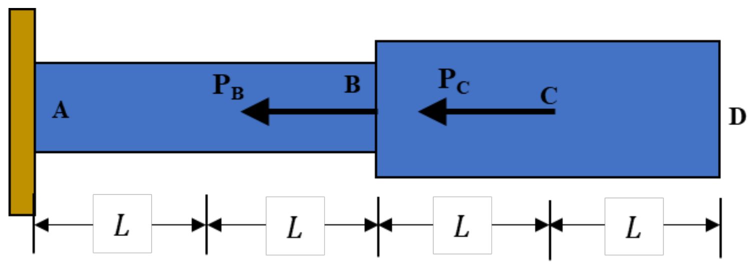


Figure 7: Physical materials supplied in the packet. Numbered flash cards for answering Activity 1 questions in class (left) and 3D model for Axial Loading module and corresponding apparatus(right)

Once a group was finished solving a problem, they were asked to raise the card that corresponds to the answer they chose from the answer choices provided. The students were also asked to record their answers on at least one group packet. As the groups displayed the corresponding cards, the implementation team recorded the responses for each group as well. An example of the Axial Loading module's Activity 1, Intervention 3 is shown in Figure 8.

Question 2

A nonprismatic bar is loaded with a force at C. Segment AB has a square cross section and segment BD has a circular cross section with diameter D. Both Segments have a Young's Modulus E. Develop the equation for displacement, δ, of the bar at C.
Assume:



Which answer is correct? Hold up the correspondingly colored card.

$$\delta = \frac{(P_b + P_C)2L}{EA_{BC}}$$

$$\delta = \frac{(P_b + P_C)2L}{EA_{AB}} + \frac{P_C L}{EA_{BC}}$$

$$\delta = \frac{(P_b + P_C)L}{EA_{BC}} + \frac{P_C L}{EA_{CD}}$$

Figure 8: Example of the Intervention 2 and Intervention 3 structure of Activity 1

Each problem presented during Activity 1 included concepts that students were exposed to during lecture in the course and would need to solve more advanced problems. This activity was developed to help the students think about the necessary steps for solving advanced concepts they may be exposed to. At the end of the five minutes allocated for each of the problems, the instructor-of-record briefly showed the correct answer and explained why the answer is correct. The students were asked to record their work in the packet for Activity 1 so their thought process when arriving at an answer could be observed. In Intervention 4, the implementation instructor explained the correct answer. The students were asked to return their work on paper from Activity 1 so their thought process when arriving at an answer could be observed.

4.3.4. Activity 2

In Intervention 1, Activity 2 was a self-guided experience for students to compare the deformation of a beam based on differences, such as cross-sectional area. Students completed three parts of the activity: Predict, Experiment, and Reflect. *Predict* the behavior of the structures before applying force. *Experiment* (Figure 9) with the structure by applying force and calculating key values. *Reflect* on whether the behavior met their expectations.

Part 2: Experiment

Set up the apparatus with the first bar's fixed end on one end and pulling mechanism on the other, as shown in the slides projected in the classroom.

Use your hand to experiment with applying axial load to one of your prismatic bars, while being careful not to break it. Follow and complete the prompts below.

When finished, talk to your neighboring group about their findings and report them in Bar 2.

Complete all answers in SI units.

	Bar 1	Bar 2
How much did the bar elongate (δ)?		
What is the normal stress in the bar after deformation (σ)?		
What is the axial strain experienced in the bar (ε)?		
What is the max possible load applied by the experimenter (P)?		

Figure 9: Activity 2, Part 2: Experiment for Axial Loading Intervention 1 structure

Incorporating the student feedback and observations throughout Interventions 1 and 2, Activity 2 was transformed to a guided step-by-step group activity for the Intervention 3 design. The new format of Activity 2 consisted of one long, advanced problem, similar to one that students might encounter in exam or homework. The problem has an accompanying multi-material 3D-printed model and apparatus to hold the model. This 3D-printed model is a physical representation of the theoretical structure shown in the problem, which students can physically interact with and deform. It is hypothesized that this physical hands-on interaction will help foster better intuition for the theory. Seeing the physical part and its behavior will help the students visualize deformation, qualify it, and understand why boundary conditions have certain constraints attached to them. The implementation team instructed students to set up the apparatus with the part(s) as shown in Figure 10b and Figure 10c, apply the loads shown in the problem given (Figure 10a), think about the behavior of the part under loading, and consider how the observed behavior compares to what the students expected.

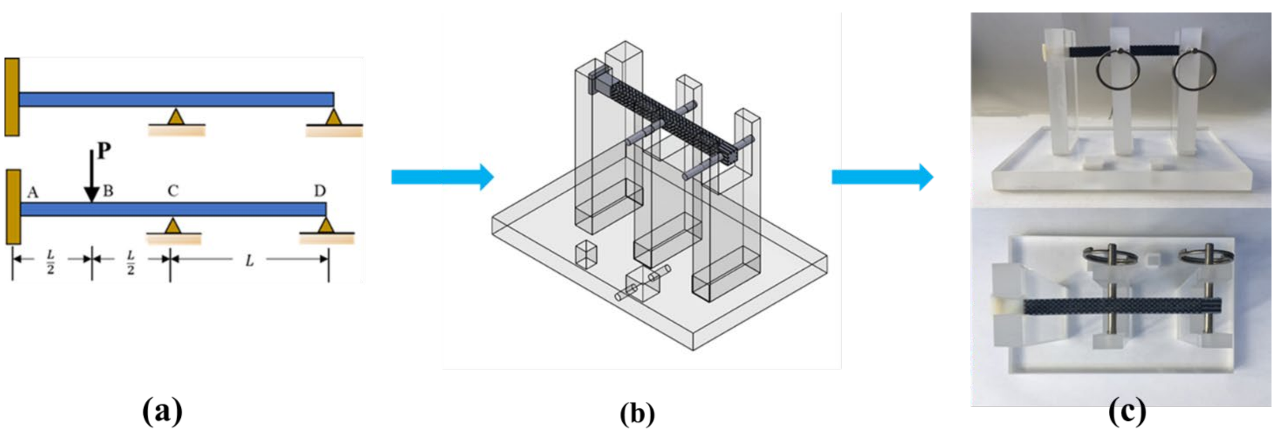
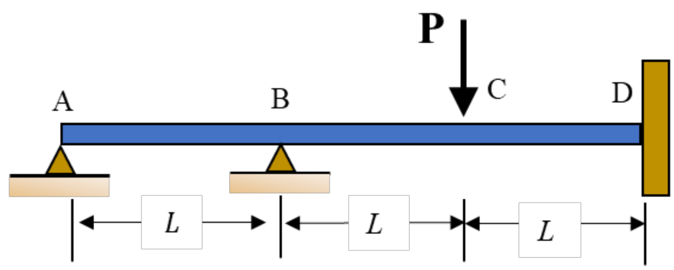


Figure 10: Translation of Beam Deflection Diagram (a), to CAD model (b), to hands-on apparatus (c).

After applying loads and observing the behavior of the physical 3D part, students work to solve the given advanced problem on paper. The problem given is adapted from a previous exam question and can be broken down into seven or eight steps to solve it methodically. The students worked in groups to solve the problem, while the implementation team guided the students through the problems if they needed help.

A beam ABCD having a rectangular cross section is fixed on one end and pinned on the other. The third support is pinned in the middle. The load is applied at point C. EI is constant throughout the beam.



Use the method of superposition to find the reaction force and moment at D. Complete the following steps to analyze the beam. (For simplicity, assume L=1m)

Figure 11: Activity 2 base problem for the Beam Deflection module

Although many of the prior exam questions are done with variables, the feedback received from piloting indicated that students felt they learned better when they were able to calculate answers using numerical values to reach a solution. Each module had a base problem (Figure 11) that gave the assumptions and explained the structure before the group moves to the analysis steps. The problems had 7-8 steps that built upon each other to reach a solution, which students were guided through step-by-step. The first step for all module topics was to develop the free body diagram for the structure. The diagram is a fundamental step to help break down what forces and loads are being applied to the beam, bar, or shaft given. The rest of the steps instructed students to calculate essential values, such as displacement, stress, strain, force diagrams, internal forces, etc. This breakdown is necessary to help the students understand the information needed in order to reach the correct solution. The students worked through the steps of the problem within their small groups. After the time allocated to group work elapses, the instructor-of-record worked through the steps of the problem to show the students the correct process. After class is over, the students were given videos and full, drawn-out answer keys to help them process the answers post-class for studying purposes.

4.3.5. Activity 3

Activity 3 was a unique, but short-lived portion of the active-learning modules that incorporated the real-world application of the module topic. This activity was intended to be an activity in which the student groups used the question to apply the topic to an assigned scenario. Each scenario was a picture of an item or structure of items the students should have encountered in their life, such as a bike (Figure 12). This portion was only included in the Intervention 1 module structure. This was discontinued for use in the subsequent modules due to class implementation time and relevance to the course materials for exams and homework.

In this activity, you will relate the theoretical concept of axial loading to real world scenarios. On the next page you will see three real world examples involving axial. Take a look at your assigned scenario and discuss the following questions (recording your answers below).

Please indicate your assigned scenario (Circle one) 1 2 3

a. Where does axial loading occur in this picture? Will it need an extra force to occur?
b. Identify the structural member(s) and the load(s) acting on it.
c. Is the structure you identified in tension or compression? What direction will the resulting displacement be in?
d. Draw the free body diagram to represent your scenario

Figure 12: Activity 3 example from Axial Loading module for Intervention 1

4.3.6. Post-Assessment

Table 5: Post-Assessment Surveys for Each Deployed Module for Intervention 3 Structure

Module Deployment	Post-Assessment Surveys
Axial Loading	Post-Module Feedback for Axial Loading Self-Efficacy for Axial Loading Concepts Perceived Value Survey
Torsion	Post-Module Feedback for Torsion Self-Efficacy for Torsion Concepts Perceived Value Survey
Combined Loading	Post-Module Feedback for Combined Loading Self-Efficacy for Combined Loading Concepts Perceived Value Survey
Beam Deflection	Post-Module Feedback for Beam Deflection Self-Efficacy for Beam Deflection Concepts Perceived Value Survey
No Module (Final Exam)	Post Exam Survey for Combined Loading and Beam Deflection

Post-assessment surveys for Intervention 3 and Intervention 4 were the same for every module (Table 5) targeted to measure the impact of the module, gather feedback, measure potential changes in self-efficacy, and to understand the perceived value to the students of different parts of the module. The Post-Module Feedback survey asked how the module impacted their knowledge, for their feedback on the strongest and weakest features, and for their opinion of the overall usefulness of the module. The self-efficacy survey was the same as used in the pre-assessment. The Perceived Value survey asked about their participation in and opinion of the module. The time allotted for this post-assessment was five minutes, after which all distributed materials were collected, and class was dismissed. The post-assessment for Intervention 1 and Intervention 2 included the Knowledge Assessment.

4.4. Intervention Components

In the intervention, along with the activity, there were many active learning components incorporated into the deployments to help aide the students' learning objectives. The 3D model and apparatus and group work helped the students visually and analytically absorb the steps to solve the problems outlined in Activities 1 and 2. The instruction and slide deck was considered and implemented in the modules to help guide the students' thought process and assist with any mental road-blocks along the way.

4.4.1. 3D Model and Apparatus

The apparatus and 3D-printed model were intended to help the students develop a physical and visual intuition for how structures deform, the different boundary conditions and why they exist, and the impact of applying different loads on the structure. Along with the acrylic base and vertical supports of the apparatus, the 3D-printed model, shown in Figure 10c, was an essential part of the module.

4.4.2. Apparatus Design

The acrylic apparatus was used to exert the boundary conditions for the 3D model, which, together was a physical representation of the complicated and abstract problems that students will encounter. The apparatus was comprised of an acrylic rectangular base with three rectangular holes in it. The three holes were used to place vertical supports, also made from acrylic. These vertical supports were interchangeable and could include fixed and pinned supports for different boundary conditions, as well as holders for the structures for stability (Figure 13). The vertical supports were used to help replicate the abstract representation of problem they were solving in Activity 2.

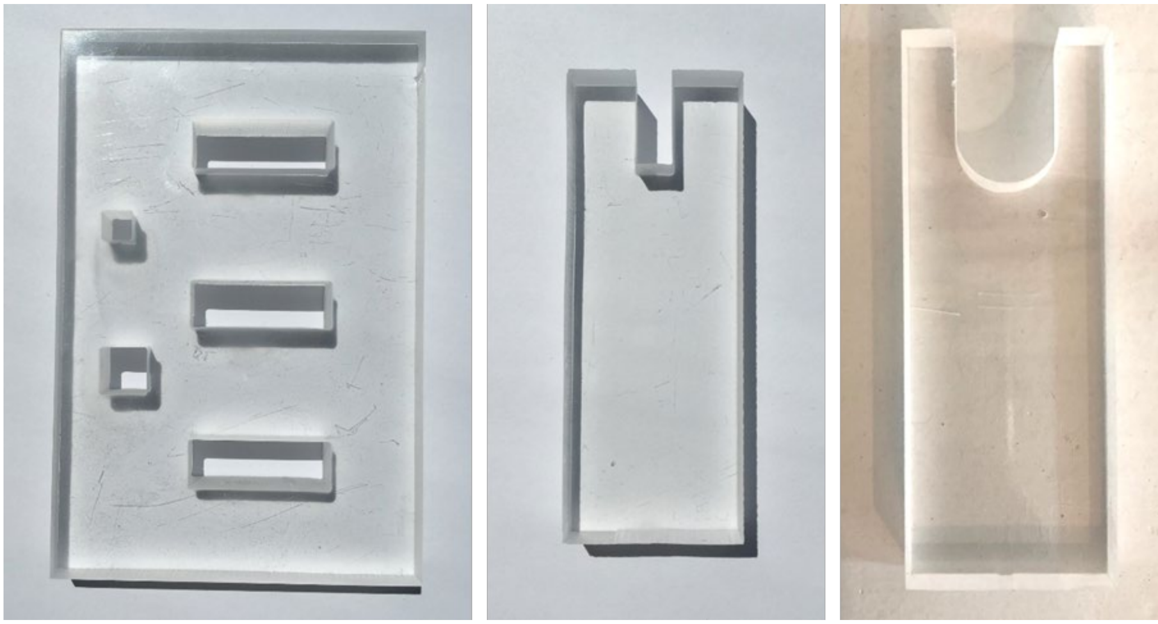


Figure 13: Acrylic Apparatus base (left), fixed vertical support (middle), and Torsion 3D part vertical support (right)

The design of this apparatus allowed potential future users and instructors the flexibility to develop a different 3D-printed models and boundary conditions to help with visualization of a wide variety of problems. The base and supports were created on Adobe Illustrator and converted to a file used for the OMAX waterjet. The acrylic being cut via waterjet allowed for multiple apparatuses to be cut-out at one time. The base was 4-inches wide and 6-inches long. The other dimensions of the apparatus are shown in Figure 14. The design of the acrylic apparatus was not altered throughout the lifetime of the project and the design iterations. Fortunately, it was designed to have multiple uses for structures outside of the four topics in mechanics of materials.

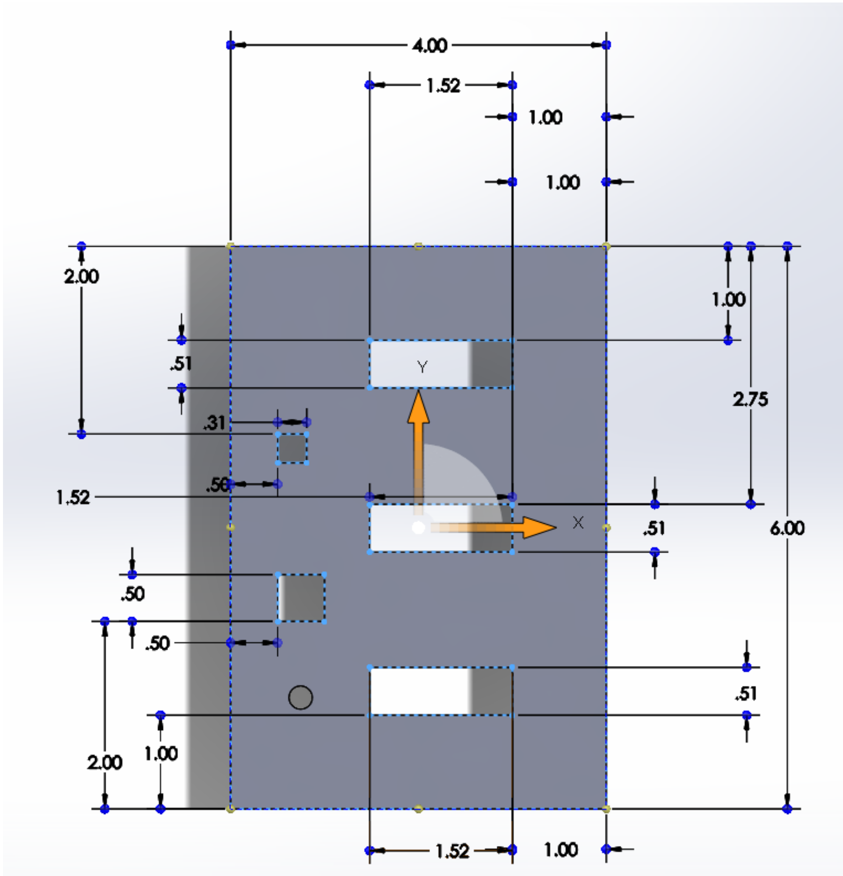


Figure 14: Apparatus dimensions

4.4.3. Evolution of the 3D model

The 3D-printed model is made of multiple materials (flexible or rigid) to facilitate the necessary physical behavior and boundary conditions that are represented in the given problem scenario from Activity 2. TangoBlack, the darker flexible material, is mixed with VeroWhite, the lighter rigid material, to create the 3D-printed model. The broken grid and supports are made from pure VeroWhite to provide stability to the part at its fixation points and to create color contrast with the dark gray to help with visualization. The 3D-printed model is subjected to loads, such as torques, axial and transverse, by the students as they experiment with it during the activity.

In Intervention 1, the 3D printed multi-material model was a simple representation of a structure for the topic of the module (i.e., a hollow tube for torsion). These models were developed with a connected grid. After the students manipulated the parts, the rigid VeroWhite Grid would break apart from the TangoBlack variation of material. This rendered the models useless after one use and was not cost effective for the classroom setting. The models were developed in this manner for Stress and Strain, Axial Loading, and Torsion for Intervention 1. The designs evolved with the evolution of the Activity 2 problem, which involved a change in the structure being analyzed. For Intervention 4, the models used were the ones from Intervention 3. These modules were manipulated, and the deformation behavior was recorded as a video from different angles.

4.4.3.1. Stress and Strain 3D Models

For the sole Stress and Strain module, there were three 3D printed models that were used for physical representations, shown in Figure 15. These models were designed to help the students visualize stress from compression and tension and strain from shear stress. The three 3D blocks were created with a base that fit into the apparatus' square hole for support (Figure 16). This allowed the 3D part to stand on its own be manipulated. The rectangular prism was designed with two VeroWhite components at the bottom, top, and in a broken grid. When the students applied a force along the top support of block, the part shifted gradually sideways. This allowed the students to visualize what it means for a structure to experience shear stress and the resulting behavior of the structure.

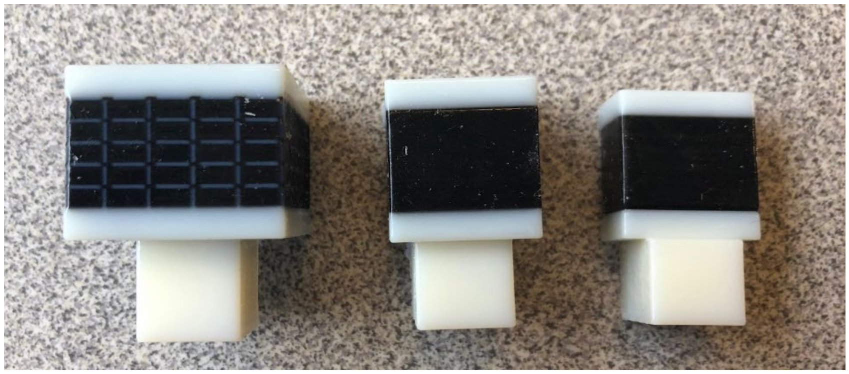


Figure 15: 3D blocks for Stress and Strain module

The other two 3D blocks for the module were used to help students understand the basic behavior of a structure subjected to tension or compression. There were two different sizes of the blocks for the students to compare the behavior of the structure when the area of the block is different. The 3D block was created in the same manner as the shear block, but it was half the width and included no grid on its surface. This was done due to the properties of the mixed TangoBlack and VeroWhite and how flexible the material was. The 3D block was intentionally flexible so the behavior of the structure would be exaggerated, so it can be seen by the eye, when it experienced stress through tension or compression.

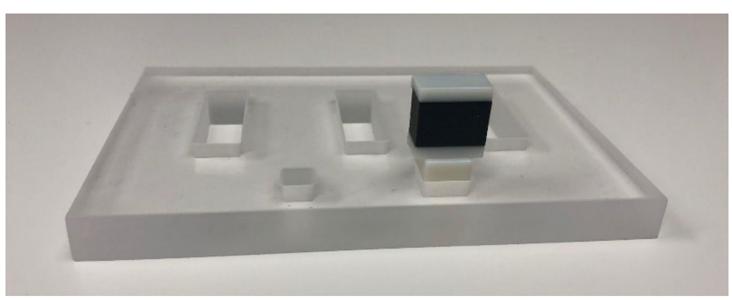


Figure 16: Apparatus with 3D block for Stress and Strain module

4.4.3.2. Axial Loading 3D Models

For the Intervention 1 Axial Loading module, there were two 3D printed models created for the activities. One model was developed as a cylindrical prism, and the other was printed as a rectangular prism. On one end, the models included a VeroWhite support for a fixed end and the broken grid. On the remaining end, the structures had a pull tab on them. This was included because the students were asked to apply load to the structures in the axial direction, and the students needed a support to apply the load. The models were developed to be comparison pieces for the students to help them see how various cross sections acted under identical loads. Figure 17 shows the example the Axial Loading and Torsion 3D models.

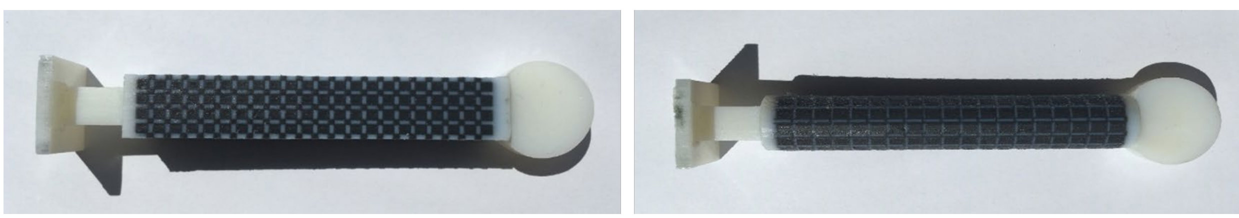


Figure 17: Axial loading module 3D printed model (left) and Torsion module 3D printed model (right)

The Axial Loading 3D model for Intervention 2 and beyond was drastically different. The model was designed for the example problem the students were given to solve in the activity. This was done to help bridge the work the students did to a real-life visual example of the forces applied. The 3D printed model, shown in Figure 18, was a two-area, non-uniform a rectangular prism structure that reached 3 inches in length. This structure was a direct representation of the problem, which required three forces to be applied to the structure. For the students to apply the forces, the model included force application supports at the three necessary cross sections; the forces were represented in the Activity 2 picture.

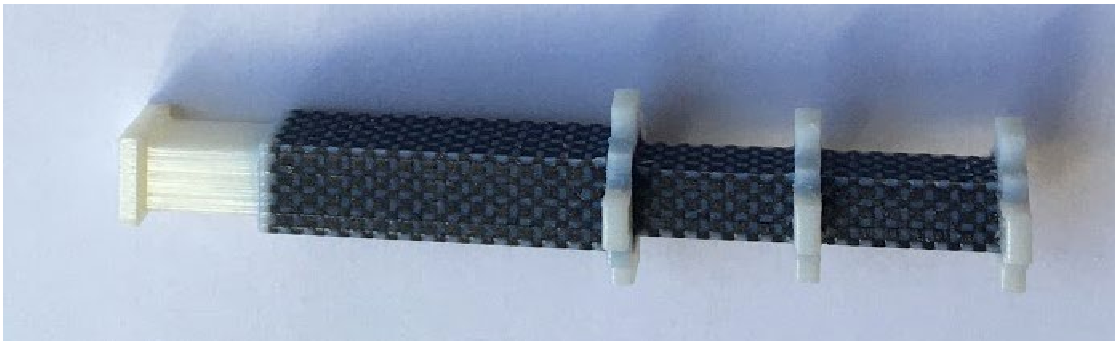


Figure 18: 3D printed model for Axial Loading module with VeroWhite grid as guidelines and force application supports

4.4.3.3. Torsion 3D Models

Similar to the Axial Loading 3D part, the Torsion module parts evolved from the self-guided type of problem to a representation of the Activity 2 problem with force application supports. Intervention 1 Torsion 3D models were two cylindrical parts, shown in Figure 19Figure 18. One of the cylindrical parts was filled with the VeroWhite/TangoBlack mixture for flexibility. The other cylindrical part was halfway hollow in the length direction. These parts were developed in this manner so the students would have two different 3D models compare torsional reaction behavior and angles of twist.

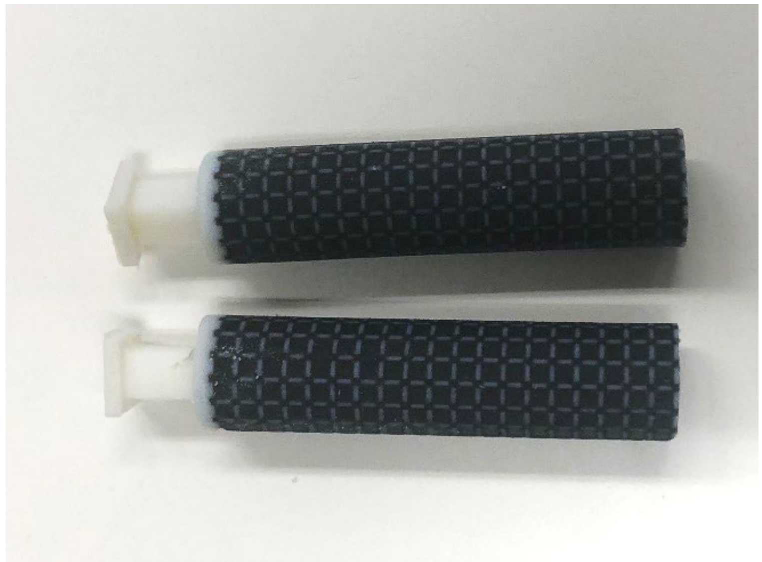


Figure 19: Torsion 3D printed models for Intervention 1

For Intervention 2 and beyond, the torsional part was created to be a representation of a non-uniform structure with two fixed ends and torque application supports at two cross sections where torque would be applied. The structure was two cylindrical structures of differing diameters, shown in Figure 20. One cross section of the structure has a distributed torque applied to it; therefore, the model incorporates a VeroWhite torque application support in the same cross sections the problem required.

Figure 20: Torsion 3D printed model for Interventions 3 and 4

4.4.3.4. Beam Deflection 3D Models

The beam deflection model was printed after Intervention 2 was introduced; therefore, the features of the 3D model were more well thought out when the module was deployed. The Beam Deflection Activity 2 problem consisted of a beam with one fixed end, pinned in the middle, and pinned on the other end. The structure did not need force application supports since the force would be applied perpendicularly to the primary axis. The two pinned cross sections of the beam were accomplished by creating a hole outlined with VeroWhite in the beam for metal pins. The pins went through the acrylic apparatus, the beam, and out the other side of the acrylic apparatus. The structure behavior was seen from looking at the side of the apparatus. Figure 21 shows the constructed 3D model and apparatus.

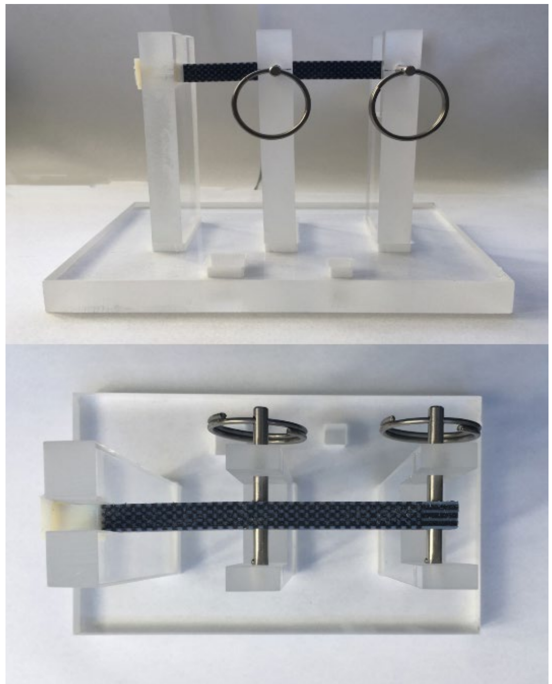


Figure 21: Beam Deflection Apparatus and 3D printed model constructed for Intervention 2 and later

4.4.3.5. Combined Loading 3D Models

The Combined Loading 3D model was developed to be a representation of a bike pedal (Figure 22). Unlike the other 3D models explained above, this model spanned two different axial directions. The structure was fixed on one end, and free on other end, where the force was applied. The structure was developed with one of the more flexible TangoBlack and VeroWhite mixes. When the force was applied, the students would be able to see the behavior of the individual parts of the structure due to the broken grid that would distort based on how much force was applied at the point of interest. This 3D model was subjected to torsion, beam deflection, and axial loading.

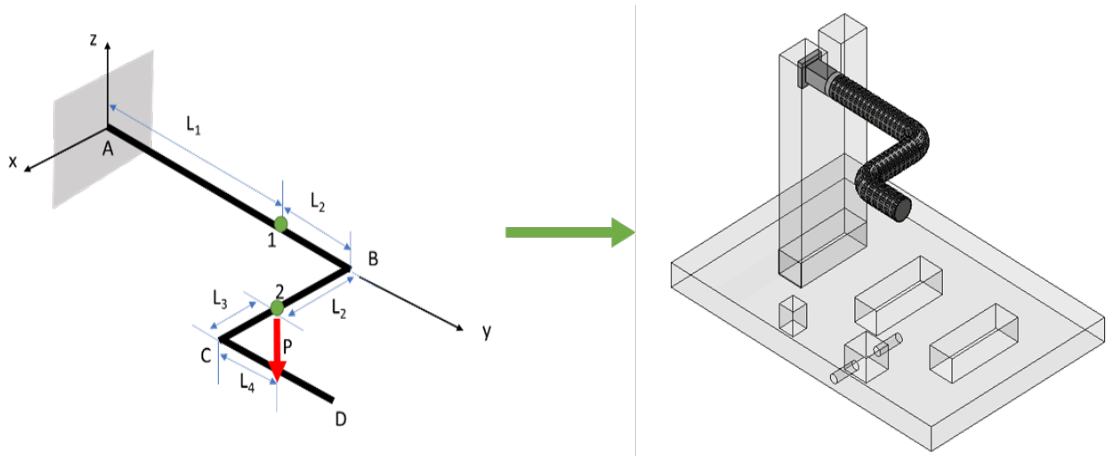


Figure 22: Combined Loading module problem and the corresponding 3D CAD model with apparatus

4.4.4. Group Work

Students worked in groups for the module activities. Groups were created by extracting the class roster, sorting out the consenting and non-consenting students, and randomly assigning group numbers to the students. Once assigned, the groups were designed to remain stable throughout the Intervention period. This random assignment helps avoid students grouping together who know each other and are familiar with their peers' capabilities in classes, which could skew the results. Three to four students were assigned to each group. On the day of the deployment, the students were asked to go into their assigned groups. When the students were looking for their group members during the class, sometimes the students were not present, and some finalized groups were different than the ones assigned. However, on days when the attendance was lower, the groups were shuffled on an ad-hoc basis to ensure that no student worked by themselves.

4.4.5. Instruction

Instruction was one of the most important factors for successful module deployment. The implementation team comprised of multiple members: deployment instructor, a teaching assistant, an undergraduate student, and an observer. In each module deployment, there were at least two members of the implementation team in the room helping with the modules. The deployment instructor served as the main person of contact in the classroom regarding the module during the class period, going over instructions, explaining the objectives of the study, and explaining the solutions to the problems. Throughout the module implementations, the responsibility for explaining the solutions switched between the deployment instructor and the instructor-of-record. The change in instructors helped understand the impact of the instruction on the students and their participation.

In Interventions 3 and 4, the structure resulted in the deployment instructor being the main point of contact for the students, with the class's main professor there for support. In the Intervention 1 and Intervention 2 deployments, the instructor-of-record was not present when the implementation team deployed the modules in the class. The students were left with the deployment instructor; somebody unfamiliar to teach and engage the class. This changed with time due to the feedback and observations. The feedback received was not all expressed explicitly, it was observed through behavior. When the instructor-of-record was present in class, the students were more likely to participate, and less likely to be uninterested. The students were more receptive to the explanations of the problems more when the instructor-of-record was present and active in the modules. The instructor-of-record helping with explanations was one of the major changes students gave feedback on and deemed valuable.

4.4.6. Slide Deck

Each module has a corresponding slide deck that was incorporated. The slide deck is a familiar method that allows the students to have a presentation similar to the traditional lectures that are conducted by the instructor-of-record. The purpose of the slide deck is to explain the instructions, so the students aren't confused about the activity. During the activity, the problems are projected onto the main classroom screen and when the time comes to explain the answers, the instructor works through the problem like they would in their normal lecture. This slide deck allowed for all the participants to obtain the same answers and be able to ask the instructor questions outside of their group settings.

4.5. Observations Evaluation

Since the evaluation was designed to be formative in nature [90], the evaluation team observed class participation and student responses during each deployment during Interventions 1 & 2. The evaluator paid attention to and compiled detailed observations on:

- Class attendance
- Student participation and engagement (in group and in individual tasks)
- Implementation approach
- Instructor presence and participation

For the purposes of the class observations and project implementation, the Logic Model in Figure 23 determined the evaluation team's expectations.

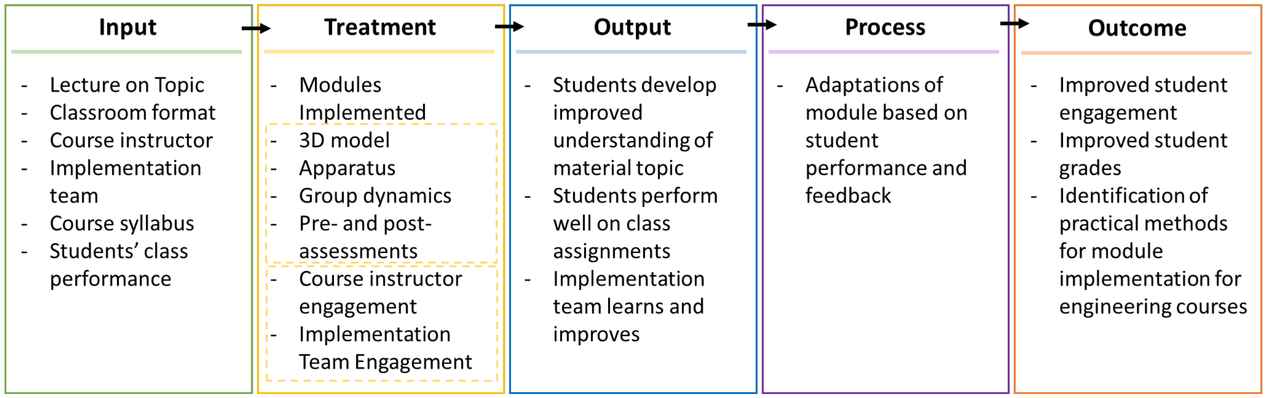


Figure 23: Logic Model for Project Design and Expected Goals and Outcomes

After every module deployment, the evaluation and implementation teams met for a debriefing session, exchanging notes, and deciding on the future course of action for the next module deployments. The evaluation team provided feedback in the form of detailed memos summarizing class observations and offering suggestions for the implementation process.

4.5.1. Student Participation and Engagement

During Intervention 1, the class participation declined over the course of the three modules. The decline in student engagement was particularly evident during the third module deployment when many students left the classroom. Since class attendance was not mandatory for the intervention implementation, students' presence could be used as a proxy measure of engagement and participation. The decline in participation, combined with student feedback was a major driver for the iteration in the design and implementation and, ultimately, the development of Intervention 2.

Student engagement varied based on the groups/teams as well as the activity being deployed. In the first intervention design, student engagement was highest during the individual pre- and post-activity assessments. During the semester, students started building a rapport with their teams and assuming established roles. However, the declining student participation during the first iteration challenged the implementation and evaluation teams' ability to interpret findings of group engagement and dynamics during the first iteration.

This stage of evaluation also highlighted the importance of providing regular feedback. Students articulated the need for both individual and group activities. However, during this stage of the implementation process, the deployment team was facing competing time pressures.

4.5.2. Implementation Team

During the rounds of in-person intervention deployment, the evaluation team noted the student responsiveness to the implementation team. During group activities, the student teams would often raise their hands and engage in one-on-one interactions with the implementers. Additionally, some students' willingness to stay on beyond class time and engage with members of the deployment team and the course Teaching Assistant highlighted that the implementation team itself was an important part of the deployment.

4.5.3. Instructor Participation

Instructor participation was identified as an important component of the intervention. Students sought clarification regarding variables included in the worksheets, additional guidance on the group activities, and, in some cases, stayed beyond class time to provide feedback in person. This finding was important in adapting to student participation and engagement, since instruction and teaching the material were part of the treatment itself. Informed by the student-instructor relationship and observations during the first three module deployments, the instructor-of-record was present in the classroom during the second iteration of the Intervention and the successive Interventions. Another related observation in the first Intervention design was the lack of intersection between the regular lectures and the Intervention modules. It appeared in the first Intervention design, that students were not at a point where they could meaningfully engage with the activity.

Additionally, from student behavior, it appeared that the instructor-of-record was not referring to or engaging with the module contents, thus creating a rift between students' perceptions of what would help with their course grades and engagement in the module. This gap also highlights the importance of structuring Intervention deployment in coordination with class instruction of the theoretical concepts related to the topics.

4.6. Feedback Results

Demographic surveys were deployed every year, but not all participants chose to disclose their demographic information. Table 6 breaks down the simple statistics for all three semesters. For Fall 2019's deployment, only 14 of the 42 total participants gave demographic data due to this survey being an online survey at the students' leisure. The demographic surveys for the following semesters were distributed with the packeted materials during the first module, therefore the students were more willing to complete the information. The majority of participants identified as male, white, in the age range of 20-22, and in the 2^{nd} or 3^{rd} year of their undergraduate studies. Most participants were mechanical engineering or aerospace engineering majors.

Table 6: Demographic survey data for Fall 2019, Spring 2020, and Fall 2020 deployment semesters

	Fall 2019	Spring 2020	Fall 2020
Total Participants	42	44	23
Demographics Survey Participants	14	42	23
Gender		**% of population**	
Man	71.4%	57.1%	78.3%
Woman	28.6%	40.5%	21.7%
Transgender; non-binary		2.4%	
Age Range			
17-19	35.7%	14.3%	30.4%
20-22	28.6%	83.3%	60.9%
23-25	28.6%	2.4%	4.3%
26-28			4.3%
29-35	7.1%		
Race/Ethnicity			
Asian, Native Hawaiian, or Other Pacific Islander	35.7%	16.7%	17.4%
Black or African American	14.3%	7.1%	17.4%
Hispanic or Latino		9.5%	4.3%
White	35.7%	50.0%	56.5%
2+ Races	14.3%	16.7%	4.3%
Year of Undergrad			
2	28.6%	28.6%	21.7%
3	42.9%	47.6%	60.9%
4	21.4%	21.4%	13.0%
5	7.1%	2.4%	4.3%
Major			
Aerospace Engineering	14.3%	28.6%	8.7%
Chemical Engineering		2.4%	0.0%
Civil Engineering	7.1%	11.9%	13.0%
Electrical Engineering		2.4%	0.0%
Environmental Engineering		2.4%	4.3%
Material Science and Engineering		11.9%	26.1%
Mechanical Engineering	78.6%	40.5%	47.8%

4.6.1. Focus Group Feedback

The feedback received from the focus groups was broken down per module. In the focus groups, the 10+ open-ended questions yielded significant insight. When transcribing the answers and comments, there were categories that the comments were broken down into: Best Parts, Difficult Parts, Improvement Suggestions, Learning, and Pace/Timing. Aside from the categories, the climate of the comments was categorized as positive, negative, and neutral. This allowed for the comments to be filtered and analyzed for impactful aspects and suggestions for future modules. The positive comments centered around the engagement of the modules, the hands-on model, and the real-world examples in Activity 3. The neutral comments on the group dynamics included suggestions, such as changing Imperial to SI units for the problems, transforming Activity 1 to definitions/terminology, and incorporating another model for the students to compare deformation scenarios. The negative comments were related to clarity of the figures and directions, the vagueness in Activity 2 and Activity 3, and the lack of congruence between knowledge assessment and module topic. The focus group feedback allowed the researchers to understand the difficulty of the modules, what parts are engaging, and how the students believed the modules impacted their knowledgebase. This led to changing the pre- and post-assessment, Activity 1 was changed to problems instead of an example fundamental concept, and the vagueness of the module language was addressed.

4.6.2. Deployment Feedback

Student feedback was collected during the deployment using a post module survey. Adopting an approach similar to that used in the focus groups, the study team disaggregated and coded the feedback. There are notable differences in the mechanisms and intent of the focus groups and module deployment questionnaires. The survey at the end of each deployment included specific questions, unlike the open-ended questions during student focus groups. These questions prompted students to describe the strongest feature, what they disliked about the module, and suggestions for future modules. Since the questions directly sought responses for "positive" and "negative" comments, the climate/sentiment of the comments was not analyzed in the module deployment data. The comments were disaggregated into four main categories: *Active Learning, Module Content, Module Structure*, and *Instructor/TA*. The active learning category comprises subtopics where the students respond to questions on group dynamics, dealing with the 3D model, practice problems, and student perceptions. The *Module Content* category is for the comments that talk about the included content of the modules and the specific *Activities*. The *Module Structure* category talks about the structure of the activities or suggestions on how the structure should be in the future. Table 7 shows comment category breakdown for the Fall 2019 semester.

Table 7: Comment feedback breakdown from Fall 2019 semester module deployments.

Comment Category	Stress and Strain (I1)	Axial Loading (I1)	Torsion (I1)	Beam Deflection (I2)
Active Learning	**43**	**19**	**19**	**17**
Feelings/Confidence	9	2	5	9
Group Dynamics	6	3	2	1
Model	22	10	10	5
Practice Problems	6	4	2	2
Instructor/TA	**2**	-	-	**15**
Instructor	2	-	-	9
TA	-	-	-	1
Instruction	-	-	-	5
Module Content	**21**	**23**	**18**	**15**
Activity 1	4	2	1	5
Activity 2	2	6	7	3
Activity 3		6	1	
Content		4		
Content (Clarifying)	11	2	6	5
Content (Overall)	4	3	3	2
Module Structure	**25**	**10**	**13**	**26**
Structure	19	3	9	13
Timing	4	3		6
Answers	2	4	4	7
Total	**91**	**52**	**50**	**73**

4.6.3. Intervention 1 Feedback

For the Fall 2019 deployment, the first three modules followed the design of Intervention 1. The Stress and Strain module feedback generated 22 comments about the hands-on, 3D model. Most of the feedback highlighted that the 3D model was the strongest feature of the module. In the Axial Loading module comment feedback, the students believed that Activity 3, or the real-world examples section, was the strongest feature of this intervention structure. Although this portion was removed for timing purposes for the next intervention structure, the 3D models in Intervention 2 were developed to realistically resemble the problem in Activity 2 – therefore incorporating a real-world type of part. For the first three modules, the students commented on the structure, stating it would be beneficial if the modules were implemented after the topic had been covered in the classroom. This feedback led the implementation team to deploy the modules after the instructor-of-record covered the entire topic in class.

Many comments addressed the difficulty of the problems and the "guide yourself" style of questions for Activity 2. The students did not believe that the problems given as a topic refresher in Activity 1 were a good path into Activity 2, nor did they capture the difficulty level needed for success with the coursework. The feedback also revealed that the students did not believe that the open-ended "guide yourself" questions of Activity 2 was helpful – they wanted concrete answers instead of assuming they completed the calculations correctly based on the forces they applied.

This feedback informed a significant change in the Module Structure. Figure 24 outlines the various, significant changes throughout the process of development. Activity

1 became more interactive, and the students were able to work more as a group to accomplish the goals. The problem difficulty level in Activity 2 was increased so the problem resembled homework or exam problems with concrete numerically calculated answers that would be given to the students at the end of each module deployment. These problems were extracted from previous exams given by the professor. Although many of the prior exam questions are done with variables, the feedback indicated that students felt they learned better when they were able to calculate answers using numerical values to reach a solution. These changes incepted the Intervention 2 Structure.

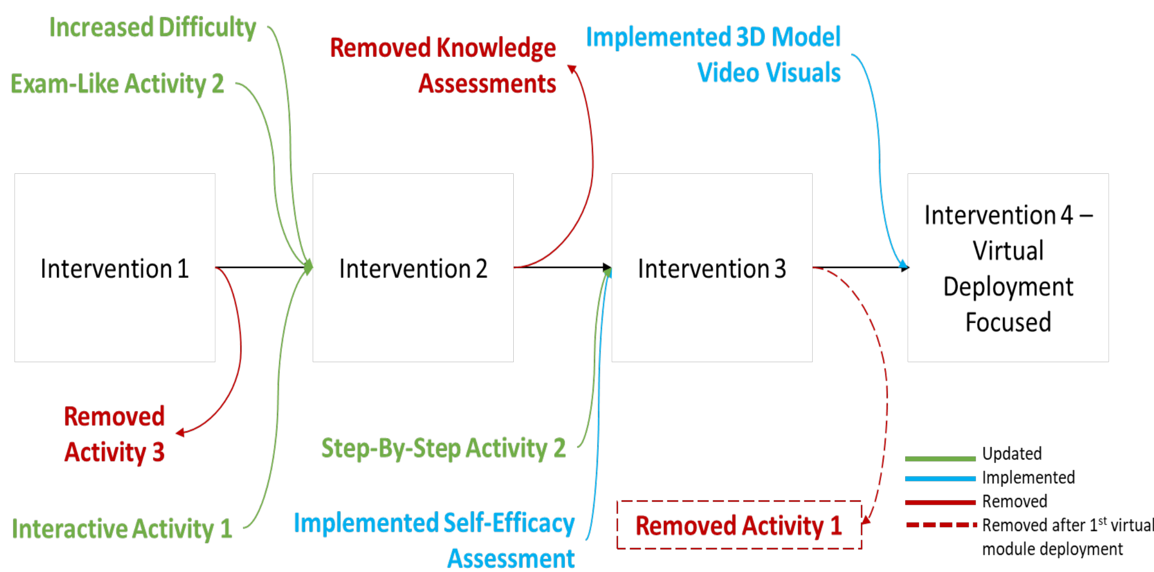


Figure 24: Flow chart of changes in module content for the four intervention structures. Intervention 4 was conducted in a virtual environment due to the COVID-19 Pandemic.

4.6.4. Intervention 2 Feedback

Intervention 2 structure was implemented in the class during the Beam Deflection section of the course. Intervention 2 incorporated many distinct changes that were deemed necessary to help the students learn the knowledge in a better environment – on paper and in the classroom. The feedback of the module revealed the students were responsive to the changes and believed that this structure was better for their absorption than the previous modules. There was a positive reaction about the role of the Instructor/TA in the module and a shift in the students' opinion on answers. The students believed that the increased presence and explanation of the problems contributed greatly to the setting of the module, in turn naming these two factors as the strongest feature, along with the 3D models. In the class, there were three people helping students with questions – deployment instructor, the teaching assistant, the undergraduate researcher, and deployment instructor researcher. The students also enjoyed the new collaborative structure of Activity 1.

The students suggested that Activity 2 should be a step-by-step guide to solving the problem, timing should be more spread out and allow more time for the students to learn the material instead being tested on it. For Intervention 3, the suggestions prompted the removal of the Knowledge Assessment to allow for more time for the module portions to be done by the students and allow for thorough explanation of the answers. Along with the time pressures, the students were increasingly frustrated with the Knowledge Assessments and their repeating questions. Although identical pre- and post-assessments are a common tool in understanding the impact of an intervention of students, it is not popular one. The suggestions also prompted the change in Activity 2, and it was broken down into every step that needed to be completed to get to the final answers.

4.6.5. Intervention 3 Feedback

For the Spring 2020 deployment, Intervention 3 was deployed for Axial Loading and Torsion modules. The Stress and Strain module was removed from the lineup because the team believed that students would have more success with the class deliverables if another, more advanced topic was focused on: Combined Loading. Because of the need for a pre-to-post quantitative measure in how the intervention impacted the students, a Self-Efficacy Assessment was implemented to help us understand the students' self-reported abilities to complete the outlined tasks. Since the assessment was not a part of the module deployment strategy, the students did not provide feedback regarding its effectiveness. Table 8 shows the feedback breakdown for the comment categories. The comments made a shift towards the Active Learning Comment Category. The students' comments focused on these topics being the strongest features. The students emphasized the beneficial nature of the interactive model and how it helped them visualize the problem in Activity 2. The interaction of the instruction team with the class was another one of the strongest features because the team worked with the students on every step, from instruction to example explanation.

Table 8: Comment breakdown from feedback of Spring 2020 deployment

Comment Category	Axial Loading (I3)	Torsion (I3)
Active Learning	**43**	**30**
Feelings/Confidence	8	10
Group Dynamics	10	6
Model	16	1
Practice Problems	9	13
Instructor/TA	**14**	**6**
Instructor	3	2
TA	8	-
Instruction	3	4
Module Content	**18**	**24**
Activity 1	3	4
Activity 2	9	11
Content (Clarifying)	3	6
Content (Overall)	3	3
Module Structure	**13**	**18**
Structure	5	4
Timing	7	9
Answers	1	5
Total	**88**	**78**

Along with the positive responsiveness comments, the students did have suggestions regarding the module structure and timing. The students wanted more time for solutions as well as more time dedicated to challenging, test-level questions.

4.6.6. Intervention 4 Feedback - Virtual Deployment

The Fall 2020 deployment constituted a significant share of the overall feedback. The comment breakdown is shown in Table 9. Comparing the Axial Loading module and the Torsion module feedback, the distribution of the comments shifted from most of them being about the *Active Learning* elements of the module to the *Module Structure* and what would be more beneficial for future deployments. The students touched on the technical difficulties on the video platform that was used and gave suggestions about where time should be focused, since the class period was only 50 minutes. Overall, the students reported enjoying the ability work in groups and the in-depth explanations of the complex problems in the first two modules. The feedback in the next two modules - Combined Loading and Beam Deflection, shifted back to the *Active Learning* elements of the modules. The students noted the change in their understanding of the topics the ability to ask questions to help with comprehension during the modules.

Table 9: Comment breakdown from feedback of Fall 2020 deployment

Comment Category	Axial Loading (I4)	Torsion (I4)	Combined Loading (I4)	Beam Deflection (I4)
Active Learning	**13**	**1**	**1**	**1**
Feelings/Confidence	2		1	
Group Dynamics	5	1		1
Visuals	2			
Practice Problems	4			
Instructor/TA	**2**	**1**	**2**	**1**
Instructor	2	1	1	1
TA			1	
Module Content	**1**	**0**	**0**	**0**
Content (Overall)	1			
Module Structure	**9**	**12**	**1**	**1**
Structure	3	4		
Timing	2	2		
Answers	1	6	1	1
Virtual Environment	3		1	
Total	**25**	**14**	**4**	**3**

4.7. Discussion

In the early stages of the study, the design and implementation teams made significant changes to the module structure to align the activities with the needs of the students and the classroom environment. Originally (Intervention 1), the team expected the students to view the modules as a steppingstone for absorbing the information in the subsequent lectures on the topic. To increase the effectiveness and impact of the intervention, the module structure was adapted for deployed after a topic was covered in the class. This change in implementation timing and structure led to many improvements in the perception of the modules by the students and the acceptance. This finding illuminates the question raised by Natarajan et al. [91] regarding the sequencing theory and practice when designing classroom interventions in engineering curricula.

4.7.1. Importance of Collecting Feedback

There are different ways of collecting crucial information to help gauge the engagement of the students and the usefulness of the project. The pilot study and focus group interviews conducted before module deployment informed the design process, and the most efficient way of obtaining feedback was through short-answer written answers. During deployment, the team primarily relied on post-module surveys to seek student feedback. These surveys revealed changes that students needed. The team also deployed a post-exam survey to collect feedback on the usefulness of the modules for attempting exam problems. The surveys consisted of both multiple choice type, Likert scale-based questions and free response questions.

Different ways of collecting data provide very different types of feedback and module design approaches. The study team noted the importance of using mixed methods of collecting data to inform all stages of study design, implementation and evaluation [87, 92, 93]. During the design process, discursive and qualitative approaches, such as interviews and focus groups, can help shape the modules. In the implementation phase, combining scale-based questions with more reflective questions can help provide a better understanding of the students' perceptions. Supplementary descriptive questions can also inform adaptative and responsive intervention development.

Finally, non-participant in-class observations complement student surveys. Revealed student responses through subtle behavior, such as group engagement, and obvious reactions, such as departing the classroom, provided an early indication and allowed the implementation team to respond by adapting the interventions. Operationally, having the evaluation team present in class during deployment allowed for a collaborative and developmental approach to evaluation during the course of implementation process. Based on the in-class observations, the evaluation team was also able to provide suggestions during the iterative design process in the study.

4.7.2. Intervention Shifts

Many factors were used to determine the necessary adaptations to make the interventions more useful for the students. According to Black and Williams (2010), knowledge learned about the progress and difficulty of their students should lead to adaptation of the teacher's work to meet the students' needs. First, there were multiple deployments of the same intervention structure to help understand what did and did not work through feedback and observation. Declining student engagement and adverse feedback for the first three modules led the design team to adapt and respond in real time, causing the shift from Intervention 1 to Intervention 2. The design team adapted Activity 1 from a review of topics to an interactive, conceptual multiple-choice activity with the student groups participating together and with the whole class. In addition, the overall level of difficulty of the module was increased, and the implementation sequence was changed to follow class lectures rather than precede them. This shift in the structure lead to a significant change in students' acceptance of the Intervention. The students identified the refined Activity 1 as one of the strongest features.

In the feedback on Intervention 2, most of the suggestions related to the Activity 2 problem. Although the difficulty of the Activity 2 structure was increased, students reported that the directions were still not very clear. In response, the team further developed a step-by-step breakdown of the problem to reach the necessary calculations for the specific problem type for Intervention 3. These steps were applicable to most problems in their homework and tests. As for the timing of the implementation of the module in the class, the students were less confused as they had seen the material in the lectures instead of guessing on what to do. The structural changes were done when there was more than 2 weeks between the prior topic being taught and the next topic being taught to give time for the module to be reworked and thought out instead of rushed.

Throughout the deployment, there was real-time adaptation to the student feedback, leading to each successive intervention being more successful. This is critical to the development of interventions because of the repetitive cycle instructors may go through to refine their intervention to enhance student participation, engagement, and performance (Black & Wiliam, 2010). Every Intervention structure change increased the share of positive feedback emphasizing the level of student engagement. Adapting to student feedback is an important component of responsive intervention design. Adaptive approaches also help understanding if a particular set of activities improve comprehension, incorporate creative ideas from the students and what they deem helpful, instead of pre-assigned tasks. The most, well thought out and informative comments arrived in the feedback after the students repeatedly tried the Intervention structure(s). This finding also led the research team to conclude that the students' comprehension of the topic could be attributed to a combination of the type of topic and the intervention design, rather than an artifact of the nature of the topic itself.

4.7.3. Adaptation over time

Making changes to long-standing core curriculum courses is often an adaptive and iterative process. This is particularly true of incorporating active learning practices in core curriculum courses such as mechanics of materials. For project success, it is crucial to adopt a flexible and responsive approach that considers all aspects related to design, production, and deployment. Additionally, expected, and unexpected effects on student behavior and learning can necessitate real time adaptive responses from the design team. This points to the need for allocating adequate resources and time for deployment, analyzing feedback, redesign as needed and recalibration.

During the initial phases of the design process, the team focused on choosing the right modules, conducting student focus groups, and preparing the apparatus and module packets. Over time, as the team's focus shifted towards deployment, the first hurdle was classroom time management, and next, understanding and meeting students' needs and expectations. In response, the team adapted by incorporating students' stated and revealed feedback and developing Interventions 2 and 3. These iterations were not only intended to improve deployment outcomes but also to align the modules better with student learning and preparing them for homework and examinations.

To summarize, over time, the team's focus shifted from practical preparations and logistical concerns to substantive refinements and fine tuning toward student learning goals and expectations. It is important to note the cumulative lessons learnt and incorporated over time. The long-term nature of the project allowed the design and deployment team to collect evidence before, during and after module deployment. Further, the iterations in Intervention design process were cumulative in nature where each successive intervention carried forward the changes from the previous design.

4.8. Strategies for Implementation

The team learned several crucial lessons learned throughout the semesters that have led to key strategies for developing and implementing in-person active learning interventions using 3D multi-material printed parts into the mechanics of materials classroom instructions.

1. **When developing the module, use a creative approach by showing students a physical representation of the problem(s) they are solving, regardless of whether it is an over-exaggeration.** These 3D model visuals will allow the students to understand the theory while practicing types of forces being analyzed to help draw a connection to real-world applications.
2. **Cater the information in the module to that which the students will need to successfully complete the formative and/or summative assessments in the class.** The module serves as another form of concept practice and benefits the students by guiding them on how to approach problems. When developing, the students will benefit from an interactive, full-class response type of activity, such as Activity 1 in the Interventions 2 and 3. The students will be able to work diligently together to reach an answer and raise their cards. This allows for a different type of class

engagement than the typical day-to-day lecture participation act of raising one's hand to ask or respond to questions.

3. **For implementation, clearly articulating the objectives of the class activity so the students understand the expectations from the activity helps gain buy-in.** Having multiple members to help implement the module is crucial. Usually, a Teaching Assistant or a helper who is familiar with the topic can help reduce the burden and move through the activities efficiently. This also gives the students a sense of belonging and more than one person to talk to if they have a question or concern.
4. **Most importantly, along with the implementation team, the instructor-of-record is best accepted as the person who explains the activities and the solution to the problems.** This gives the students a familiar face who they will listen to, and respect, and their presence will influence the students to stay, even when the activity is not mandatory.
5. **During the activities, listen and observe the students and their behavior.** The students' body language and amount of participation will reveal the participants' engagement, responsiveness, and any changes that the behavior may reflect (i.e., group changes, alterations to 3D models, etc.).

Although the focus of this study was primarily in-person implementation, the virtual deployment offers some strategies for adapting and deploying the modules.

1. **When developing the modules or adapting them to the space, preparing additional video visuals for the materials models that accompany the problem can be used a substitute for tactile interaction with the materials.** This will help

the students develop a visual sense of the application of the force(s) or other impact the model is subjected to in the problem(s) given.

2. **When choosing the platform for implementation into the class, ensuring the platform is conducive to breakout rooms so the students can participate in the activity in smaller groups and return to the main room when the allocated time ends is important.**
3. **Implement the guided step-by-step activity**, or Activity 2, in the class only to give the students more time to work through the problems before the instructor's explanation.
4. If time and the platform allows, **implementing a multiple-choice activity**, such as Activity 1, **in the beginning can be a useful tool for providing the students an interactive, engaging environment**.
5. **While in the class, visit all of the breakout rooms like one would in the classroom, but have somebody stay back into the main room just in case the students go to the main room for help** (similarly to if the student comes to the front to ask the instructor a question).
6. **Allocating sufficient time to work through the problem(s) of the module in the class to allow students to feel that they know what they are doing or to correct their mistakes**.
7. **Offering an answer key and an explanation video to help engrain the concept.**

4.9. Conclusions

Development of a sound active learning intervention structure that incorporates multi-material 3D models, their corresponding apparatuses, and group learning for a core concept in mechanical engineering has had challenges and successes. This paper was written to outline the challenges faced, how they were overcome, and recommended strategies for future implementations. The successes for the module development and implementation stemmed from listening to the students, where they struggled, and what they deemed would be a better fit for learning the course materials. Incorporating the students in the process allowed for more robust modules and increased satisfaction with in-class activities. Although many challenges around retention and engagement existed in the beginning and during the virtual deployments, the strategies for implementation are shared here to help future researchers figure out how to use these activities as lectures and enhance the students' understanding and scores. The factors used for changing the intervention structure throughout the years allowed for open, need-based changes, resulting in a concrete structure that can be used in multiple different topics of the mechanics of materials class in the future.

The development of these modules spans across multiple semesters and incorporates significant topics in the class. The modules utilize active learning and group collaboration to assist students in conceptualization and visualization in mechanics of materials. The development process of these modules is extensive, and measuring the impact is important. The 3D apparatus incorporates technology that is unique compared to current activities in undergraduate classes. The models are novel because of the ability to use the multi-material 3D printer to print gridlines and force application supports for students to manipulate the samples while visualizing deformation. The next deployments of the modules will contribute to the viewpoint that the development process of hands-on learning activities in an engineering classroom are just as important as the evaluation of student outcomes.

CHAPTER 5. MODULE IMPACT ON STUDENT OUTCOMES

The purpose of this chapter is to breakdown and explore the student outcomes from the three semester deployments of the modules and the multiple changes in Intervention structures. This chapter will give the quantitative impact of the iterative development outlined in the previous chapter. The breakdown of the student surveys and class assessment data will reveal if the interventions were effective and if there were any trends present that determined student success. This chapter will examine the trends in each semester, plus the between-semester comparisons trends.

5.1. Comparison of Semesters

Since the intervention deployment spanned multiple semesters and three different intervention structure changes, there are various methods to compare the data obtained from the many self-reported surveys. This section will broadly compare the information from the Post-Module survey within the semesters and across multiple semesters. The students were asked to agree or disagree with the statements on a 5-point Likert-scale (1- Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 – Strongly Agree).

5.1.1. Fall 2019

The four modules deployed in Fall 2019 were pilots in the classroom. The first three (Stress and Strain, Axial Loading, and Torsion) were deployed in the Intervention 1 structure outlined in the previous chapter. The last module (Beam Deflection) was deployed using the Intervention 2 structure.

Figure 25: Fall 2019 comparison of average Post-Module survey responses; Error bars show ± one standard deviation shows the comparison of the averages of the post module answers for each of the four modules. Intervention 1 modules are shown in blue, and the Intervention 2 module is represented in green. From this comparison, it can be concluded that the students were least comfortable with the subject matter of Beam Deflection and the Beam Deflection intervention activities contributed most to their understanding. This result shows either the topic of Beam Deflection was difficult to comprehend as a concept, or the structure change to Intervention 2 had a sincere impact on the student's understanding of Beam Deflection. Axial loading was a module with which the students were most comfortable and felt as though the activities contributed to their understanding of the subject matter. Stress and Strain and Torsion were modules with which the students weren't as comfortable, and the activities didn't contribute to their understanding of the subject matter as much as was hoped. For the Stress and Strain and Beam Deflection modules, there was not an Activity 3, therefore it is not included in the averages in the figure. The Intervention 2 structure of Beam Deflection excluded Activity 3 when it was developed.

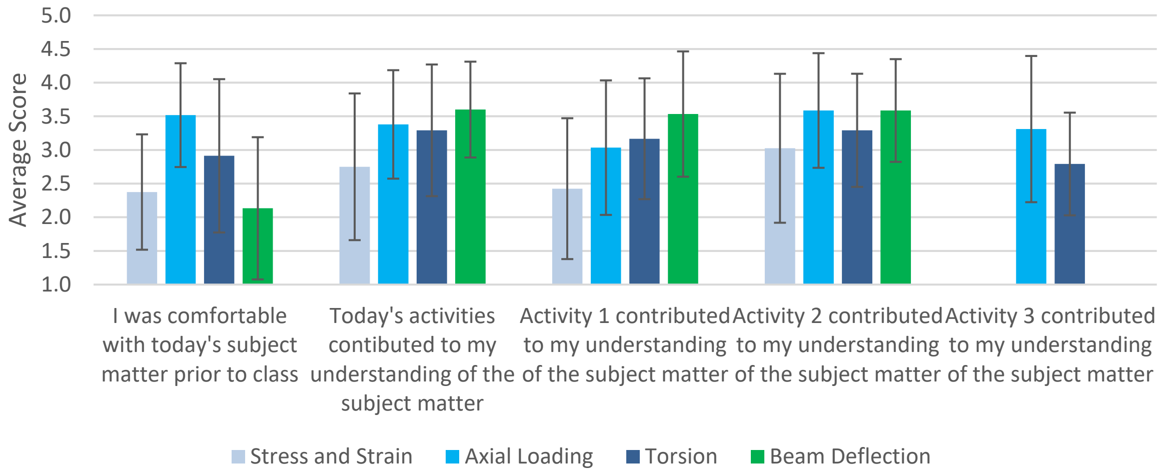


Figure 25: Fall 2019 comparison of average Post-Module survey responses; Error bars show ± one standard deviation

5.1.2. Spring 2020

In Spring 2020, there were two modules deployed in the Intervention 3 structure. This structure changed because it didn't include Activity 3 and broke down the steps to the advanced problem in Activity 2. According to Figure 2, the Axial Loading module had more of an impact on the students' understanding of the knowledgebase compared to the Torsion module. Most of the averages of the Axial Loading module are greater than 4.0, which corresponds to "Agree" in the Likert scale. Although the Torsion module averages weren't far off from those of the Axial Loading module's, it can be assumed that the students felt that both modules did have a profound impact on their knowledgebase.

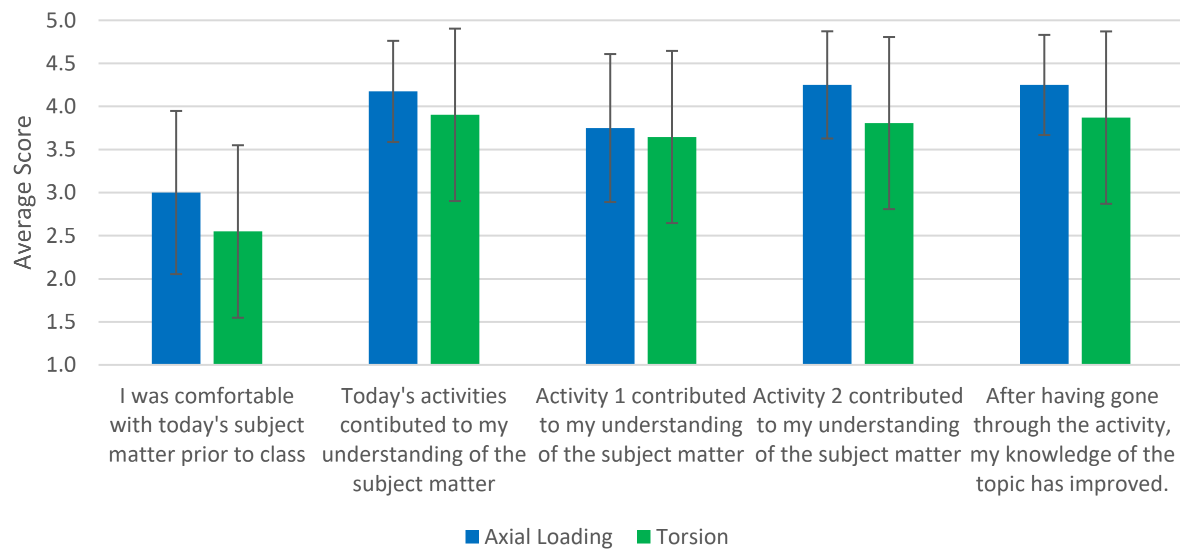


Figure 26: Spring 2020 comparison of average Post-Module survey responses; Error bars show ± one standard deviation

5.1.3. Fall 2020

Fall 2020 was different from the other semesters because the modules had to be adapted for virtual learning. This involved great changes to the information and activities being provided. In the Axial Loading module, there were two activities the students believed contributed to their understanding of the subject matter. Unfortunately, the retention of the students decreased drastically from the first module to the end modules, but the trend of student attendance was similar to the class attendance at the end of the semester. There were two students who responded to the virtual Post-Module surveys for Combined Loading and one respondent for the Beam Deflection Post-Module survey. Due to the lack of responses, the responses for Combined Loading are broken down later in the chapter, and the responses for the Beam Deflection module are not analyzed and compared.

The data, shown in Figure 27, reveals the students were not comfortable with the respective subject matter, but the activities did make more than a “neutral” impact on the students’ understanding and their knowledge of the topic.

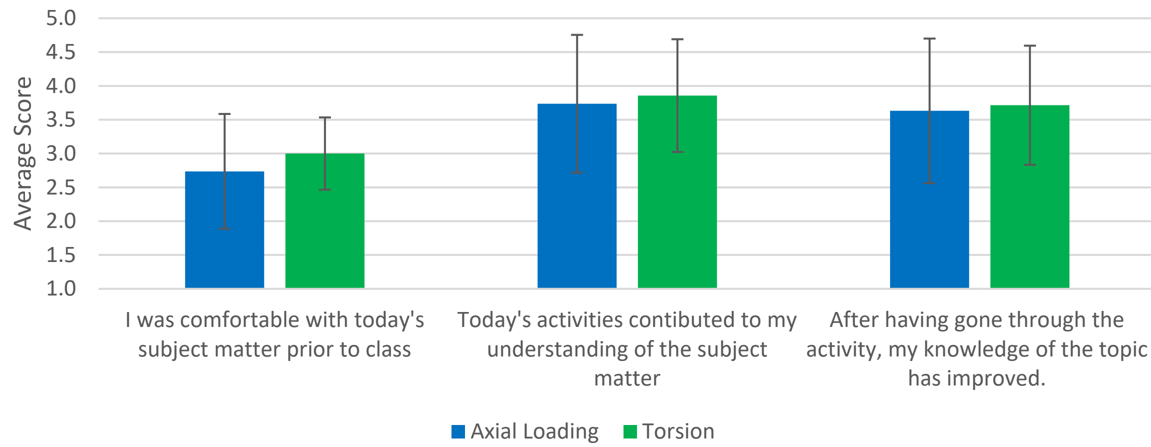


Figure 27: Fall 2020 comparison of averages of Post-Module survey responses; Error bars show ± one standard deviation

5.1.4. Between Semesters Comparisons

There were two modules deployed in all three semesters: Axial Loading and Torsion. Although the Intervention structures changed from semester to semester, the comparison of the self-reported impact of the modules by the students is important. For both modules, Fall 2019 had the Intervention Structure 1, Spring 2020 had the Intervention Structure 3, and Fall 2020 had the Intervention Structure 4. For Intervention Structure 4, Axial Loading was the only module with two parts: Activity 1 and Activity 2 instead of one sole activity: Activity 2.

Between semester comparisons for Axial Loading and Torsion modules are important to understand the difference in the intervention structures deployed for both topics throughout this research. For both modules, the students completed Post-Module surveys and self-efficacy surveys to help the researchers develop an understanding of the self-reported impact. In Fall 2019, the students were given pre- and post-knowledge assessments instead of self-efficacy surveys.

The Kruskal-Wallis H-test (also known as the Kruskal-Wallis 1-way ANOVA) was run for Fall 2019, Spring 2020, and Fall 2020 semester comparisons for Axial Loading and Torsion modules to determine if the students' knowledgebase was impacted differently based on the Intervention Structures. The assumptions for the Kruskal-Wallis H-test were met for all data sets because the data is non-parametric, there are three levels of independent groups, and each data set is either continuous or ordinal. Post-hoc Dunn's test with a Bonferroni correction was used to explore the significance of the pairs of semesters. The Dunn's test is used for pairwise comparisons of the independent groups and is automatically computed though SPSS.

5.1.4.1. Axial Loading Module

Figure 28 reveals that the Axial Loading Intervention 3 structure had more of an impact on the students than the other two, besides the overall rating of usefulness. This finding can imply that the in-person module with Activity 2 to break down the problem and to present the structure with a manipulatable 3D model helps contribute to the students' knowledgebase. The greatest impact was with Activity 2 with an average score of 4.3/5. This reveals that the 3D model and step-by-step breakdown of the problem was useful.

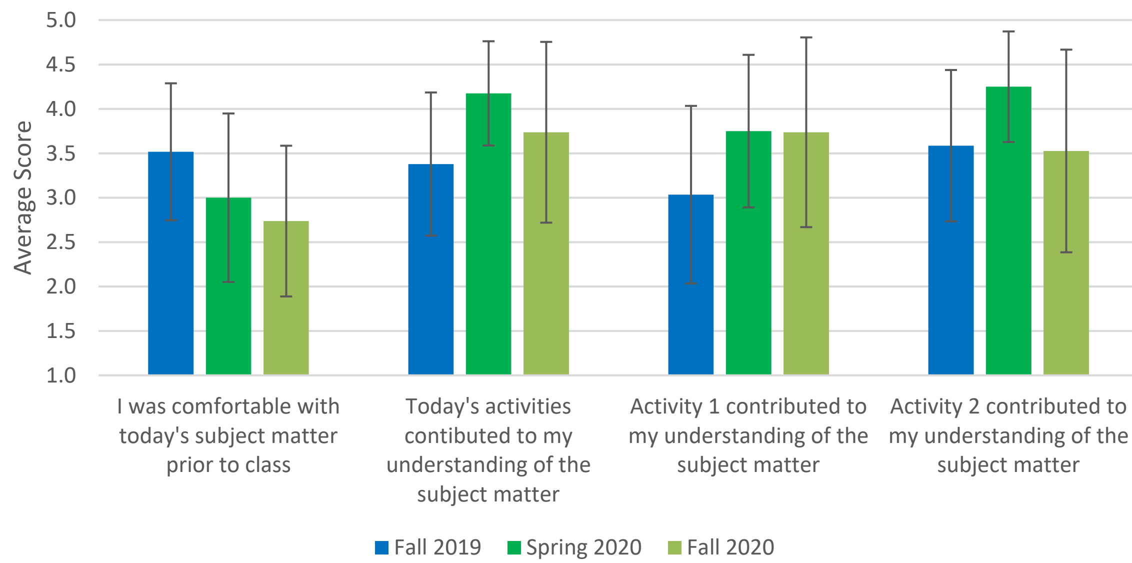


Figure 28: Between semester comparison of averages of Axial Loading module Post-Module survey responses; Error bars show ± one standard deviation

For the Axial Loading modules, the Post-Module survey data was analyzed using the Kruskal-Wallis H test because the data is non-parametric, there are three levels of independent groups, and each data set is ordinal. The hypothesis is there will be a difference between the Axial Loading Post-Module survey ratings for the between the semesters for all prompts in the Post-Module survey.

The Kruskal-Wallis H-test showed there was a statistically significant difference in the score of the statement "I was comfortable with today's subject matter prior to class" between the semesters, $H(2)=10.077$, $p = 0.006$, with a mean rank of 55.63 for Fall 2019, 41.10 for Spring 2020, and 34.68 for Fall 2020. A post-hoc test using Dunn's test with Bonferroni correction showed a statistical significance between Fall 2019 and Spring 2020, p=0.10 and between Fall 2019 and Fall 2020, p=0.41. There was no statistical significance between the distribution of answers for Spring 2020 and Fall 2020, p=1.00. Overall, it can be concluded that the students were more comfortable with the subject matter prior to the intervention in Fall 2019 than in both Spring 2020 and Fall 2020.

A Kruskal-Wallis H-test showed there was a statistically significant difference in the score of the statement "Today's activities contributed to my understanding of the subject matter" between the semesters, $H(2) = 14.971$, $p = 0.001$, with a mean rank of 32.22 for Fall 2019, 54.05 for Spring 2020, and 43.13 for Fall 2020. A post-hoc Dunn's test with Bonferroni correction showed a statistical significance between Fall 2019 and Spring 2020, $p < 0.001$. There was no statistical significance between the distribution of answers for Fall 2019 and Fall 2020, p =0.333, and between Spring 2020 and Fall 2020, $p = 0.273$. It can be concluded that the Spring 2020 Intervention 3 structure had a more profound impact on the students' understanding and knowledgebase, than on the Intervention 1 structure deployed in Fall 2019.

A Kruskal-Wallis H-test showed there was a statistically significant difference in the score of the statement "Activity 1 contributed to my understanding of the subject matter" between the semesters, $H(2)$ =10.123, $p = 0.006$, , with a mean rank of 32.86 for Fall 2019, 49.74 for Spring 2020, and 51.24 for Fall 2020. A post-hoc test using Dunn's test with Bonferroni correction showed a statistical significance between Fall 2019 and Spring 2020, $p = 0.12$, and between Fall 2019 and Fall 2020, $p = 0.030$. There was no statistical significance between the distribution of answers for Spring 2020 and Fall 2020, p =1.00. From the statistical analysis, Spring 2020's Intervention 3 Activity 1 structure had a greater impact on the students' subject matter was greater than that of Fall 2019

Intervention 1's Activity 1 structure. It can be concluded that Activity 1 contributed to the subject matter of the later semesters than the initial Fall 2019 semester.

A Kruskal-Wallis H-test showed there was a statistically significant difference in the scores of the statement "Activity 2 contributed to my understanding of the subject matter" between the semesters, $H(2) = 12.097$, $p = 0.002$, with a mean rank of 36.10 for Fall 2019, 54.00 for Spring 2020, and 37.32 for Fall 2020. A post-hoc test using Dunn's test with Bonferroni correction showed a statistical significance between Fall 2019 and Spring 2020, $p = 0.005$, and between Spring 2020 and Fall 2020, $p = 0.032$. There was no statistical significance between Fall 2019 and Fall 2020 semesters, $p = 1.00$. The results reveal that there is not a difference in the response scores of the in-person Intervention 1 and the virtual Intervention 2. This also reveals that Intervention 3 had a sincere impact on the knowledge and learnings of the students due to the correlations of Spring 2020 to the Fall semesters.

For all four of these between-semester and pairwise semester comparisons of the Post-Module survey scores, the data opens space to conclude the impact of the Spring 2020 Axial Loading intervention structure potentially had the greatest impact on the students. The Intervention structure included the step-by-step exam-like problem with a 3D model to connect the students to the real world. These results show that this could be the optimal form of the intervention, even in comparison to Fall 2020, or the virtual adaptation of the Spring 2020's in-person one.

5.1.4.2. Torsion Module

For the Torsion Module, Figure 29 reveals that the students of Spring 2020 comparatively felt less comfortable with the subject yet agreed the most about the module activities contributing to their understanding of the subject matter. This reveals that although it is a difficult topic overall, there is benefit in these Torsion modules being implemented in the class, regardless of structure.

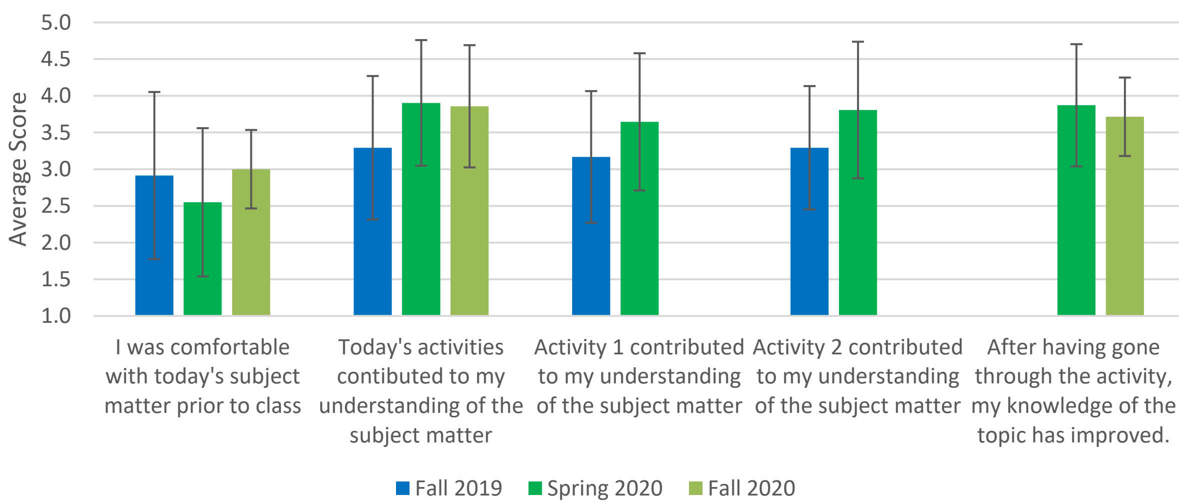


Figure 29: Between semester comparison of averages of Torsion module Post-Module survey responses; Error bars show ± one standard deviation

Although the Torsion module was deployed in three semesters, the Post-Module survey questions shifted as the number of Activities shifted. All semesters included Activity 2; or one individual Activity 2-like activity, in the case of Fall 2020. For three post-survey statements, a Kruskal-Wallis H-test was conducted. The Post-Module survey data for Torsion was analyzed using the Kruskal-Wallis H test because it meets the assumptions the data is non-parametric, there are three levels of independent groups, and each data set is ordinal. The hypothesis is there will be a difference between the Torsion Post-Module survey ratings for the between the semesters for all prompts in the Post-Module survey.

A Kruskal-Wallis H-test showed there was a statistically significant difference in the score of the statement "Today's activities contributed to my understanding of the subject matter" between the semesters, H(2) = 5.999, $p = 0.05$ with mean rank 35.63 for Spring 2020, 25.08 for Fall 2019, and 35.21 for Fall 2020. A post-hoc test using Dunn's test with Bonferroni correction showed no significant difference between pairs of all three semesters: Fall 2019 and Spring 2020, $p = 0.054$; Fall 2019 and Fall 2020, $p = 0.451$; and Spring 2020 and Fall 2020, $p = 1.000$. This finding means the null hypothesis is retained that the distributions are the same between each of the pairs of semesters for the statement.

A Kruskal-Wallis H-test showed there was a statistically significant difference in the score of the statement "Activity 2 contributed to my understanding of the subject matter" between the semesters, H(2) = 7.906, $p = 0.019$ with mean rank 37.10 for Spring 2020, 27.65 for Fall 2019 and 19.93 for Fall 2020. A post-hoc test using Dunn's test with Bonferroni correction showed a statistical significance between Spring 2020 and Fall 2020, p=0.046. There were no significant difference the other two pairs of semesters: Fall 2019 and Spring 2020, $p = 0.120$; and Fall 2019 and Fall 2020, $p = 0.865$. This finding means Activity 2 had a significant impact based on responses between the Spring 2020 and Fall 2020 semesters, or Intervention 2 and Intervention 4 structures respectively.

There was no statistical significance between the three semester scores for the statements "I was comfortable with today's subject matter before class", H(2) = 2.448,

p=0.294 and “Activity 1 contributed to my understanding of the subject matter”, H(2)=0.420, p = 0.110.

For all three of these post-survey statements, these findings reveal that the Spring 2020, or Intervention 3 semester had higher mean ranks, therefore the students agreed more with the statements. Also, the Torsion Post-Module surveys showed that there was a difference in score distribution across the board, but the change of Intervention structures from semester to semester didn’t impact the students’ responses as much as the Axial Loading module.

There were two semesters in which Activity 3 was not included in the Intervention structure, and the “Activity 3 contributed to my understanding of the subject matter” was replaced with “After having gone through the activity, my knowledge of the topic has improved” for Spring 2020 and Fall 2020. A Mann-Whitney U test was used to compare the two semesters. The data sets met the assumptions of the semester data sets being independent samples, the data being continuous, and the data failing Shapiro-Wilk’s test of normality, therefore being non-parametric. The Mann-Whitney U test indicated that the difference in scores between the Spring 2020 group and the Fall 2020 group, $U(N_{Spring\ 2020} = 31, N_{Fall\ 2020}=7) = 45$, z = -2.538, p = 0.011 was statistically significant.

This data revealed that there is a possibility that Spring 2020 Intervention 3 has a more profound impact on the students’ Torsion knowledgebase than the other intervention structures, especially the Fall 2020 virtual module structure.

5.1.5. Homework and Exam Scores

As noted in the previous chapter, Fall 2018 was used as control semester during which the students' exam and homework grades were collected. Fall 2018 had 44 students participate in the study. The semester was taught half by the Instructor of Record and the other half by an alternative instructor. The homework and exam deliverables for Axial Loading and Torsion in Fall 2019 and Spring 2020 are correlated against Fall 2018 scores. Stress and Strain and Beam Deflection homework as included in the comparison between Fall 2018 and Fall 2019. Fall 2020 was not included due to the virtual nature of the homework and the complications with running a virtual class. Also, the final exam that incorporated Beam Deflection was not compared due to the breadth of information on the exam that was not majority Beam Deflection.

A Kruskal-Wallis H test was used to show the distribution of scores across the semester for the Axial Loading homework scores, Torsion homework scores, and the first and second exams of the semester. The assumptions the data met for all three semesters were: the data is non-parametric, there are three levels of independent groups, and each data set is continuous.

A Mann-Whitney U-test was conducted on the analysis of means for pairs of semesters instead of three. The data sets met the assumptions of being independent samples, the scale being continuous, and the data failing Shapiro-Wilk's test of normality, therefore being non-parametric.

5.1.5.1. Stress and Strain

The Stress and Strain module was one of a kind and was not distributed in another semester outside of Fall 2019. A Mann-Whitney U-test was run to compare Fall 2018 and Fall 2019 stress and strain homework scores. The hypothesis is there will be a difference between the Stress and Strain Homework scores for the Fall 2018(control) and Fall 2019 semesters. The test revealed no statistical significance between the Fall 2018 and Fall 2019 Stress and Strain scores, $U(N_{Fall\ 2018} = 44, N_{Fall\ 2019} = 39) = 845$, $z = -0.137$, $p = 0.891$; therefore, it can be concluded that the Stress and Strain module may not have had an impact on the students' knowledgebase to help them succeed in their homework assignments, as compared to the Fall 2018 control group.

5.1.5.2. Axial Loading and First Exam

For the Axial Loading homework comparison, the hypothesis is there will be a difference in the Axial Loading Homework scores between the Fall 2018(control), Fall 2019, and Spring 2020 semesters. The Kruskal-Wallis H test showed there was a statistical significance of the distribution of homework scores across the three semesters, $H(2) = 6.563$, $p = 0.038$. A post-hoc test using Dunn's test with Bonferroni correction showed significant differences between Fall 2018 and Spring 2020, $p = 0.034$. There was no statistical significance between Fall 2018 and Fall 2019, $p = 1.0$, and Fall 2019 and Spring 2020, $p = 0.318$.

For the first exam comparison, the hypothesis is there will be a difference in the first exam scores between the Fall 2018(control), Fall 2019, and Spring 2020 semesters. A Kruskal-Wallis H test showed there was a statistical significance of the distribution of homework scores across the three semesters, H(2) = 14.977, $p = 0.001$. A post-hoc test using Dunn's test with Bonferroni correction showed a significant difference between Fall 2018 and Spring 2020, $p < 0.001$. There was no statistical significance between Fall 2018 and Fall 2019, $p = 0.363$, and Fall 2019 and Spring 2020, $p = 0.163$.

5.1.5.3. Torsion and Second Exam

For the Torsion homework comparison, the hypothesis is there will be a difference of the Torsion homework scores between the Fall 2018(control), Fall 2019, and Spring 2020 semesters. A Kruskal-Wallis test showed there was no statistical significance of the distribution of the homework scores across the three semesters, H(2) = 3.199, $p = 0.202$.

For the second exam comparison, the hypothesis is there will be a difference in the second exam scores between the Fall 2018(control), Fall 2019, and Spring 2020 semesters. A Kruskal-Wallis test showed there was a statistical significance of the distribution of exam scores across the three semesters, H(2) = 14.727, $p = 0.001$. A post-hoc test using Dunn's test with Bonferroni correction showed the significant difference between Fall 2018 and Spring 2020, $p = 0.010$, and between Fall 2018 and Fall 2019, $p = 0.002$. There was no statistical significance between Fall 2019 and Spring 2020, $p = 1.0$.

5.1.5.4. Beam Deflection

The Beam Deflection module was only ran in-class during Fall 2019. The hypothesis is there will be a difference of the Beam Deflection homework scores between the Fall 2018(control) and Fall 2019. A Mann-Whitney U-test was run to compare Fall 2018 and Fall 2019 beam deflection homework scores. The test revealed there is a statistical significance between the pair of semesters for the Beam Deflection scores $U(N_{Fall\ 2018} = 44, N_{Fall\ 2019}=26) = 302.5$, $z = -3.786$, $p < 0.001$. The mean rank for the Fall 2018 semester is 29.38 and Fall 2019 is 45.87. This reveals that the scores from Fall 2019 were significantly better than those of Fall 2018.

The overall results reveal the lack of difference between the Fall 2019 Intervention 1 and Fall 2018 control group scores, but there is a difference between Intervention 3 and the control group scores based on the post-hoc analysis completed. Similar to the Post-Module survey results, the students had higher scores when exposed to Intervention 2 compared to those exposed to Intervention 1 and the traditional class regarding its impact on how students performed in the class.

5.2. Individual Semesters

There were three distinct deployment semesters where information was collected for evaluation of the impact of the student activities. Each semester was unique and had circumstances that impacted long-term data collection – for better or for worse. The Limitations chapter will divulge these circumstances, but for context, a summary is given.

Fall 2019 and Fall 2020 were both semesters during which four interventions were deployed where changes were implemented during the semester. Fall 2019 consisted of full intervention framework changes from the first modules to the one towards to later part of the Mechanics of Materials course. Fall 2020 included a slight modification, which excluded Activity 1's multiple choice teamwork style activity after the first module, due to technical difficulties. Fall 2020 was also a victim of the declining retention of a virtual class setting due to the COVID-19 pandemic, which translated to the modules and resulted in drastically low attendance during module deployment days for the later part of the semester.

Although there were only two modules deployed in the intervention structure developed, the Spring 2020 semester was successful in terms of the in-person space and the level of engagement students exhibited while working through the activities.

Each semester had similar surveys: self-efficacy, learning and instruction, module perception, and post exam (when distributed). These surveys served as a baseline for the students' learning, as well as feedback on how the research team was interacting with the students and the results of the interactions. The qualitative aspects of the feedback were outlined in Chapter 4 of this dissertation.

Learning and Instruction Survey: This survey was used to obtain a general idea of how students wanted an ideal classroom to function. This information is important because it gives a baseline for how receptive the students would be to the activities. The survey used five different frequencies for the students to respond to: Never, Once a semester, Once a Month, Once a Semester, and In every class.

Self-Efficacy Survey: Self-efficacy was measured with surveys before and after the students were introduced to the intervention. The survey asked the students to rate their degree of confidence to do the tasks associated with the corresponding subject matter using a Likert scale response from 1-5 (1- Cannot do at all, 3- Moderately can do, and 5 – Highly certain can do). Self-Efficacy surveys were incorporated into the assessments in lieu of the Knowledge Assessments starting in Spring 2020, when Intervention 3 was deployed.

Module Perception Survey: The module perception survey was given to the students asking them how much they agree with the statements pertaining to the current module deployment. The statements were in two categories: the student's role and the instructor's role. The students were asked to utilize the Likert scale response to agree or disagree with the statements regarding their personal performance and the performance of the instructor(s). The purpose of collecting this information was to see if relationships exist between how the students performed on the activities. This survey's first distribution was in the Torsion module deployment of Fall 2019. The students were asked to answer the statements on a 5-point Likert-scale (1- Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 – Strongly Agree).

Post-Exam Survey: Post-exam survey was critical for the research team to hear the students in regard to how the activities impacted their ability to do the homework and the respective exams. The students were asked to utilize a Likert scale response to agree or disagree with the statements provided about homework and exams. These surveys weren't able to be distributed for the later semester module deployments of Spring 2020 and Fall 2020; they were only used to understand how the Axial Loading module impacted their ability to complete the class deliverables. Post Module Exam surveys were distributed to the students after each module to gather information on how the students believed the Axial and Torsion modules helped with their class deliverables. The students were asked to answer the questions on a 5-point Likert-scale (1- Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 – Strongly Agree). The scores for the students were averaged and compared to each other.

Post-Module Survey: The Post-Module survey is used to understand the student's stance on the activities' impact on their understanding of the subject matter. Although broken down in earlier sections, this survey has many crucial parts to help understand how many students responded. The Post-Module survey was correlated with other surveys and the class deliverables to understand any trends present for the Spring 2020 semester Axial Loading and Torsion modules. The students were asked to answer the statements on a 5-point Likert-scale (1- Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 – Strongly Agree).

5.2.1. Fall 2019

5.2.1.1. Learning and Instruction Survey Results

This survey allows for the research team to understand the type of students there were in the Fall 2019 participant pool. Figure 30 shows the distribution of the students' answers. Over 70% of the students wanted to listen to the instructor lecture during class, and 90% of students identified that they wanted to watch the instructor demonstrate how to solve problems during class. These are the typical traditional lecture-style actions the instructor takes in the classroom. About 60% of students wanted to make and justify assumptions when not enough information is provided and take initiative for identifying what they need to know once a week. This indicates the students are willing to tackle ambiguity in the problem-solving process and would like to utilize their critical thinking skills in class once a week. Roughly 25% of the students would like to solve problems in a group during class in every class and roughly 35% would like to work in groups once a week. Lastly, about 60% of the students would like to work on hands-on group activities during class once a month. This is roughly how much the students were exposed to the hands-on modules deployed in the class; therefore, the modules were widely accepted.

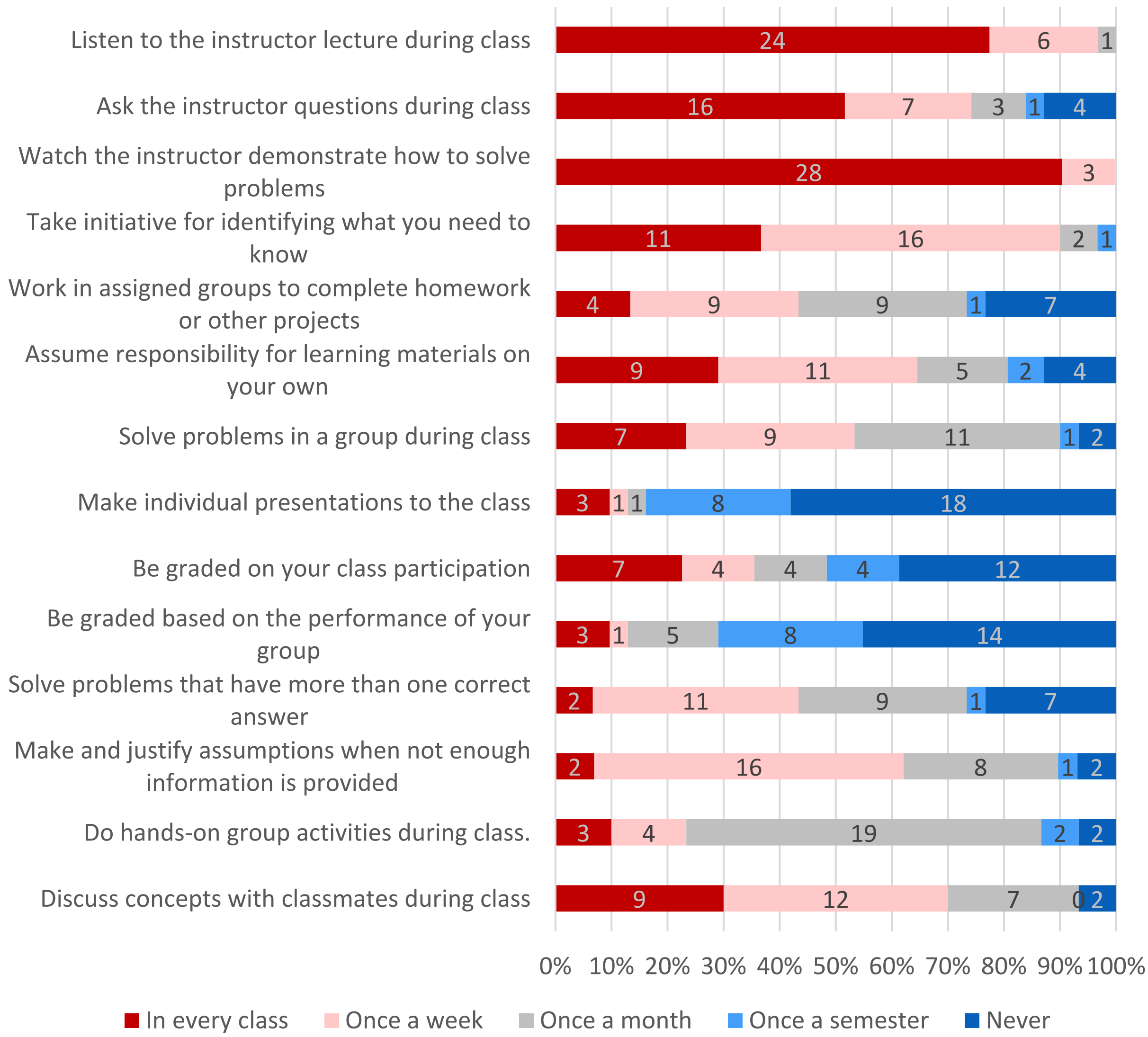


Figure 30: Fall 2019 Learning and Instruction survey responses by frequency

5.2.1.2. <u>Knowledge Assessment</u>

For this semester, the Knowledge Assessments were distributed before and after the module activities were deployed in the class. The assessment was short and encompassed some subjects the students were likely to encounter in the module activities.

5.2.1.2.1. Stress and Strain Module

For the Stress and Strain, the Knowledge Assessment consisted of three questions. The first question asked the students to draw an example of normal and shear stress, plus it asked what causes normal strain. The second question asked for the two main causes of strain and three examples of stresses and strains that we experience in everyday life. The third problem asked the students to draw a free body diagram, calculate normal stresses, and calculate normal strain.

The total possible points for the assessments was 17 points. Due to the data being continuous and matched pairs with no significant outliers, paired t-tests were conducted to compare the pre- and post-Knowledge Assessment. The hypothesis is there is a difference between the pre-intervention and post-intervention Knowledge Assessment scores for Stress and Strain. The paired t-tests were conducted for the total pre-and post-assessment scores, as well as each assessment question, and the results are shown in Table 10. Fall 2019 Stress and Strain Knowledge Assessment paired t-test results. The overall mean assessment score increased from 6.86 ± 2.85 points to 9.21 ± 3.17 points, and this resulted in a statistically significance in the change in means of the scores ($t(39) = -4.821$, $p < 0.001$). There was a statistical significance for four of the individual questions. There was a statistical significance for Question 1-2 ($t(39) = -2.489$, $p = 0.017$) which asked the students what normal strain was and how it was measured. For Question 3, all of the parts yielded a statistical significance: Question 3-1 (t(39) = -2.393, $p = 0.022$) . Question 3-2 (t(39) = -4.235, $p < 0.001$), and Question 3-3 (t(39) = -5.414, $p < 0.001$). Interestingly for Question 1-1, the students experienced a decrease in score from 2.26 ± 1.22 points to 2.03 ± 1.10 points

Table 10. Fall 2019 Stress and Strain Knowledge Assessment paired t-test results

Paired Question (Total Points)	Pre-Assessment		Post-Assessment				
	Mean	Standard Deviation	Mean	Standard Deviation	df	*t*	*p*
Overall Score (17 pts)	6.86	2.85	9.21	3.17	39	-4.821	0.000**
Question 1-1 (4pts)	2.26	1.22	2.03	1.10	39	0.570	0.572
Question 1-2 (2pts)	0.80	0.90	1.09	0.82	39	-2.489	0.017*
Question 2-1 (2pts)	0.90	0.66	1.10	0.60	39	-1.711	0.095
Question 2-2 (3pts)	1.70	1.29	1.98	1.18	39	-1.704	0.096
Question 3-1 (2pts)	0.83	0.77	1.10	0.78	39	-2.393	0.022*
Question 3-2 (2pts)	0.25	0.43	0.76	0.69	39	-4.235	0.000**
Question 3-1 (2pts)	0.13	0.33	0.84	0.80	39	-5.414	0.000**

***significant (p<0.05); **highly significant (p<0.001)**

The trends that were seen between the two assessments were that the students did not know what normal strain was and did not know how it was measured initially, for Question 1-2. In the post-Knowledge Assessment, many of the students learned the difference between normal stress and normal strain. For Question 2, the students didn't know 2 causes of strain in a structure, and they couldn't come up with many examples of stresses and strains in both the pre- and post-Knowledge Assessment. Lastly, for Question 3, the students did not do a good job deciphering the difference in equations for the normal stress and normal strain of the bar in the problem given for the pre-Knowledge Assessment.

5.2.1.2.2. Axial Loading Module

For the Axial Loading module Knowledge Assessment, there were three questions with two parts in each question. The first question asked the students about drawing and labeling a free body diagram of a bar under an axial load plus three examples of axial loading. The second question asked about St. Venant's Principle and an axial loading scenario. The last question was a problem that asked the students to solve for the stress caused by a load and the elongation that would occur.

The total possible score for the assessments was 14 points. Due to the data being continuous and matched pairs with no significant outliers, paired t-tests were conducted to compare the Axial Loading module pre- and post-Knowledge Assessment scores. Paired t-tests were conducted for the total pre- and post-assessment scores, as well as each assessment question. The hypothesis is there is a difference between the pre-intervention and post-intervention Knowledge Assessment scores for Axial Loading. Table 11 shows the breakdown of the paired t-test results. Due to the means of the overall pre- and post-Knowledge Assessment scores, and the direction of the t-value ($t(28) = -5.009$, $p < 0.001$), it can be concluded that there was a statistically significant improvement of the Knowledge Assessment scores from 9.379 ± 2.41 points to 11.483 ± 1.62 points following the intervention activities. There is a statistical significance ($p < 0.05$) in the means comparison of each individual question besides Question 1-1 ($t(28) = -1.609$, $p = 0.119$), which focused on drawing and labeling a diagram of a bar subjected to an axial force, and Question 2-2 ($t(28) = -0.769$, $p = 0.448$), which focused on the scenario of a bar under equal axial loads.

Table 11: Fall 2019 Axial Loading Knowledge Assessment paired t-test results

Paired Question (Total Points)	Pre-Assessment		Post-Assessment		Test Statistics		
	Mean	Standard Deviation	Mean	Standard Deviation	df	t	p
Overall Score (14pts)	9.38	2.37	11.48	1.59	28	-5.009	0.000**
Question 1-1 (3 pts)	2.71	0.57	2.67	0.75	28	0.246	0.808
Question 1-2 (3 pts)	1.97	1.19	2.69	0.83	28	-3.660	0.001**
Question 2-1 (1 pt)	0.19	0.38	0.50	0.49	28	-3.550	0.001**
Question 2-2 (1pt)	0.79	0.31	0.84	0.27	28	-0.769	0.448
Question 3-1 (3pts)	1.93	0.88	2.41	0.47	28	-3.221	0.003*
Question 3-2 (3pts)	1.79	0.97	2.36	0.57	28	-3.391	0.002*

***significant (p<0.05); **highly significant (p<0.001)**

There were trends that were seen in the Axial Loading Knowledge Assessments. The typical trend of making calculation mistakes, such as changing diameter to radius or the magnitude of the mega-pascal were seen constantly throughout the assessments. Additionally, many students did not know what St. Venant's principle (Question 2-1) was after the activities, yet it yielded a significant difference in the score. Question 1 and Question 2 were conceptual problems and Question 3 was the calculation part of the assessment. The students had the most problems with the conceptual pieces of the assessment. Regarding Question 3, a noted trend was the students had the process to solve the problem written down to the numerals, but they possibly needed a calculator or more time to finish the whole question.

5.2.1.2.3. Torsion Module

For the Torsion module Knowledge Assessment, there were three questions, two with multiple parts. The first question asked students to draw and label a fixed rod under torsion, define non-uniform torsion, and list three examples of torsion. The second question asked the students to calculate shear stress and angle of twist. The last question included figures, and the students were asked to identify how they would deform with the applied torques.

The total possible points for the assessment was 18 points. Due to the data being continuous and matched pairs with no significant outliers, paired t-tests were conducted to compare the Torsion module pre- and post-Knowledge Assessment scores. The hypothesis is there is a difference between the pre-intervention and post-intervention Knowledge Assessment scores for Torsion. Table 12 shows the breakdown of the paired t-test results. Due to the means of the overall pre- and post- Knowledge Assessment scores, and the direction of the t-value ($t(23) = -7.251$, $p < 0.001$), it can be concluded that there was a statistically significant improvement of the Knowledge Assessment scores from 13.02 ± 2.66 points to 16.25 ± 1.41 points following the intervention activities. There was a statistical significance between means for all question parts, excluding Question 1-1 ($t(23) = -0.901$, $p = 0.377$), which asked students to draw and label a free body diagram of a bar under torsion and Question 1-2 ($t(23) = 0.569$, $p = 0.575$), which asked the students to define non-uniform torsion.

Table 12. Fall 2019 Torsion Knowledge Assessment paired t-test results

Paired Question (Total Points)	Pre-Assessment		Post-Assessment		Test Statistics		
	Mean	Standard Deviation	Mean	Standard Deviation	df	t	p
Overall Score (18pts)	13.02	2.66	16.25	1.41	23	-7.251	0.000**
Question 1-1 (4pts)	3.63	1.11	3.75	0.83	23	-0.901	0.377
Question 1-2 (1pts)	0.73	0.38	0.69	0.38	23	0.569	0.575
Question 1-3 (3pts)	1.17	1.11	2.71	0.54	23	-6.850	0.000**
Question 2-1 (3pts)	2.38	0.62	2.58	0.62	23	-2.198	0.038*
Question 2-2 (3pts)	2.13	0.86	2.60	0.32	23	-2.361	0.027*
Question 3 (4pts)	3.00	1.53	3.92	0.28	23	-3.114	0.005*

***significant (p<0.05); **highly significant (p<0.001)**

Similar to the Axial Loading trends, students used the same examples for the Activity 3 real-world examples in the post-Knowledge Assessment question asking for 3 real-world examples of torsion. Also, the students were able to write the equations and the necessary input values down for Question 2, but the students may not have had a calculator to complete the calculations. Although that is a trend, the students still achieved higher scores for Question 2 in the post-Knowledge Assessment.

5.2.1.2.4. Beam Deflection Module

In this stage of the semester, the Beam Deflection module took a different structure than the other three modules deployed: Intervention 2. This structure was drastically different than the other three modules deployed in the Fall 2019 semester. Due to time constraints, the students were only able to complete the pre-Knowledge Assessment and do the post surveys for the module, instead of the assessment. The Pre-Knowledge Assessment scores are broken down into averages and the standard deviation for each question. The average score for the pre-Knowledge Assessment was 8.09 ± 1.74 points.

There were three questions. The first question was to derive a slope curve based on the information given. The second question asked the students to draw a free body diagram and identify the necessary cuts for analysis of a beam. The third question asked the students to identify the needed cases for analysis with superposition based on the forces and supports of the beam. The score means and standard deviations are in Table 13. There were not any noticeable trends in the work the students did for the pre-Knowledge Assessment.

Table 13. Fall 2019 Beam Deflection pre-Knowledge Assessment paired t-test results

Question Number (Total Points)	n	Mean	Standard Deviation
Overall Score (11 pts)	32	8.09	1.74
Question 1 (1 pt)	32	0.34	0.34
Question 2 (3 pts)	32	2.94	0.24
Question 3-1 (2 pts)	32	1.78	0.54
Question 3-2 (2 pts)	32	1.38	0.60
Question 3-3 (3 pts)	32	1.66	0.99

5.2.1.3. Post-Module Survey Result Distribution by Module

Although Section 7.1 compares the Post-Module response averages per statement for each module topic, this section shows the frequency of responses for each of the statements. This is important to understand how many students believed the modules helped or didn't help their knowledgebase. The following four sections breakdown the frequency of the response by module topic.

5.2.1.3.1. Stress and Strain Module

The Stress and Strain module was deployed in the Intervention 1 structure. Stress and strain may have been a difficult topic in the course due to over 50% of students not being comfortable with the subject matter prior to the activities. Figure 31 shows that less than 30% of students believed that the activities contributed to their understanding of the subject matter. Breaking down the two activities, there was a strong disagreement (52%) that Activity 1 contributed to their understanding of the subject matter. However, 40% of the student agreed that Activity 2 contributed to their understanding of the subject matter. This may have been a result of implementing the 3D models to help students visualize stress and strain in person.

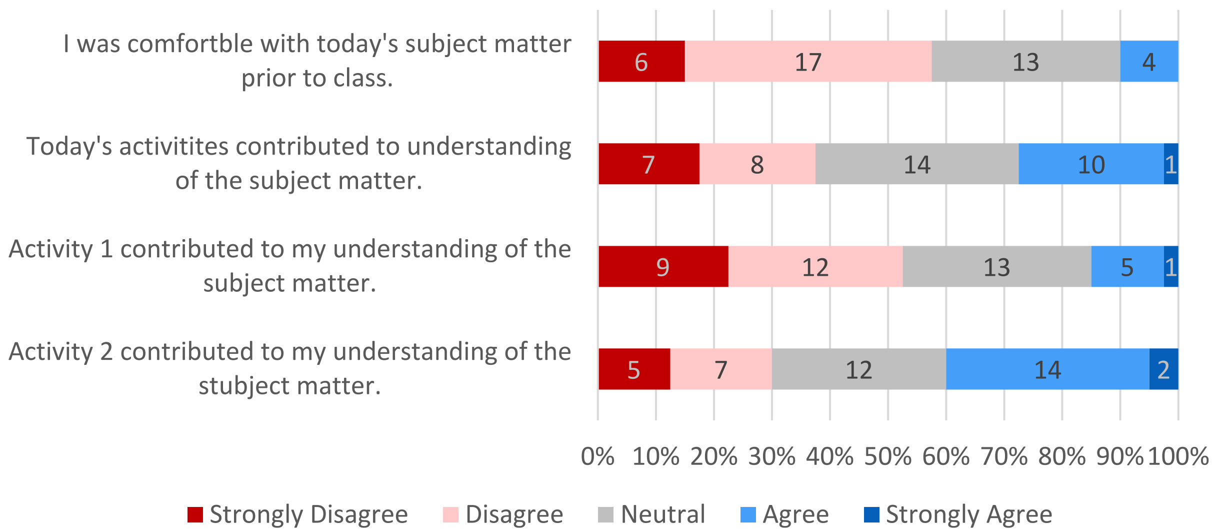


Figure 31: Fall 2019 Stress and Strain module Post-Module survey responses by frequency

5.2.1.3.2. Axial Loading Module

The Axial Loading module was deployed in the Intervention 1 structure. Unlike the Stress and Strain module responses, about 70% of students agreed they were comfortable with the subject matter prior to class. Although these students were comfortable with the subject matter, 55% claimed the activities helped contribute to their understanding of the subject matter, and Activity 2 was the part of the activities that impacted their understanding the most. It can be concluded that although the students were comfortable, that the hands-on aspects of the module were effective in helping them understand the topic a bit further than they thought they knew. Figure 32 shows the frequency of responses.

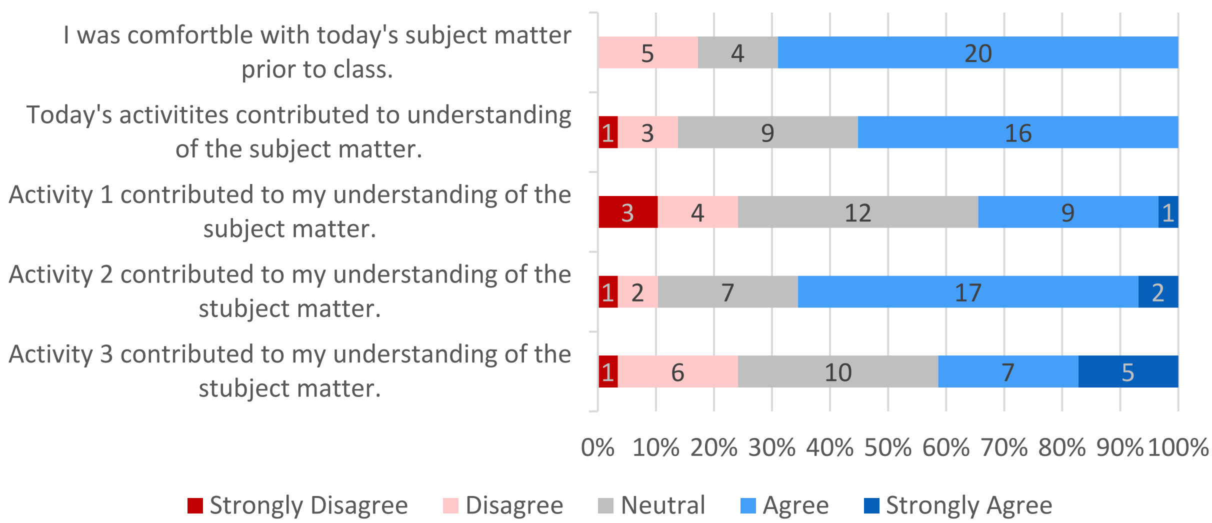


Figure 32: Fall 2019 Axial Loading module Post-Module survey responses by frequency

5.2.1.3.3. Torsion Module

The Torsion module was deployed in the Intervention 1 structure. Similar to the Stress and Strain module, the students (60%) weren't as confident with the subject matter prior to class like with Axial loading. As shown in Figure 33, 54% of the students believed the activities contributed to their understanding of the subject matter but did not believe that Activity 1 and Activity 3 contributed to their understanding as much as Activity 2. The students didn't necessarily disagree that the activities contributed; the students had a neutral stance on the statements for Activity 1 (33%) and (50%). This data reveals the students were split on their stance about how much the module contributed to their understanding of the subject matter. This prompted the change of the module structure for the Beam Deflection module.

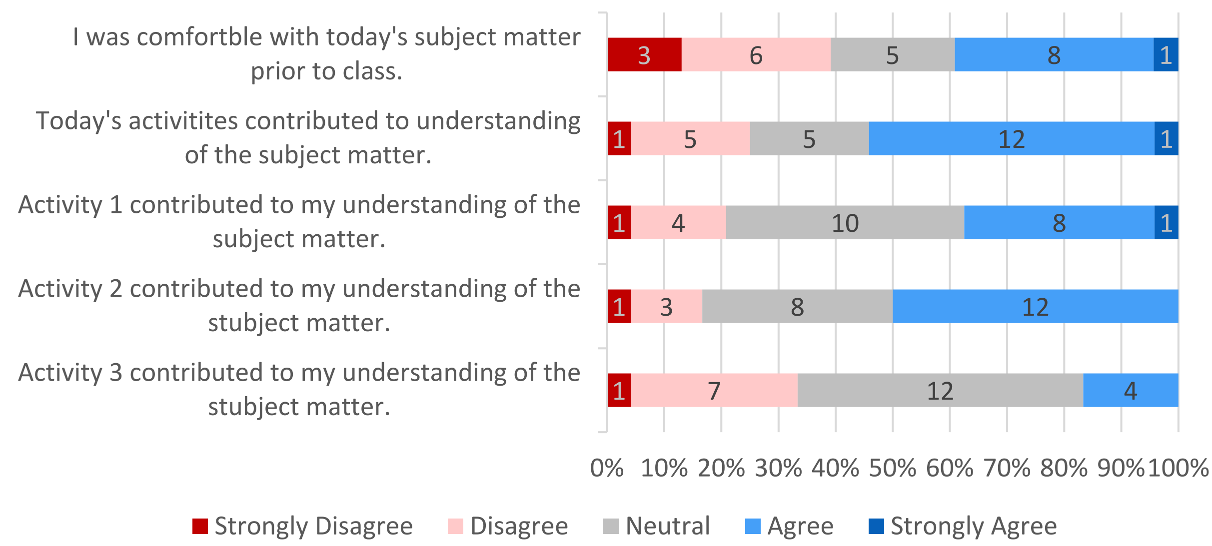


Figure 33: Fall 2019 Torsion module Post-Module survey responses by frequency

5.2.1.3.4. Beam Deflection Module

The Beam Deflection module was deployed in the Intervention 2 structure. This was the only semester in which the students saw a drastic change in the module structure. The previous three deployed modules in the semester incorporated an Activity 3 statement on the post-module survey. This post-module survey did not include this statement; instead, the survey asked how much the pre- and post-assessments contributed to their understanding of the subject matter. Interestingly, the students' responses were split evenly in regard to the statement "The pre- and post-assessment contributed to my understanding of the subject matter". 30% of the students agreed, and 30% of the students disagreed to the statement, while 33% of the students responded "Neutral" to the statement. This survey was one of the main reasons why it was decided to not move forward with Knowledge Assessments in Intervention 3. Figure 34 shows the frequency of these responses.

For the other statements, about 60% of the students agreed or strongly agreed that the activities contributed to their understanding of the subject matter. This is vastly more than the previous deployments in the Intervention 1 structure for the other topics.

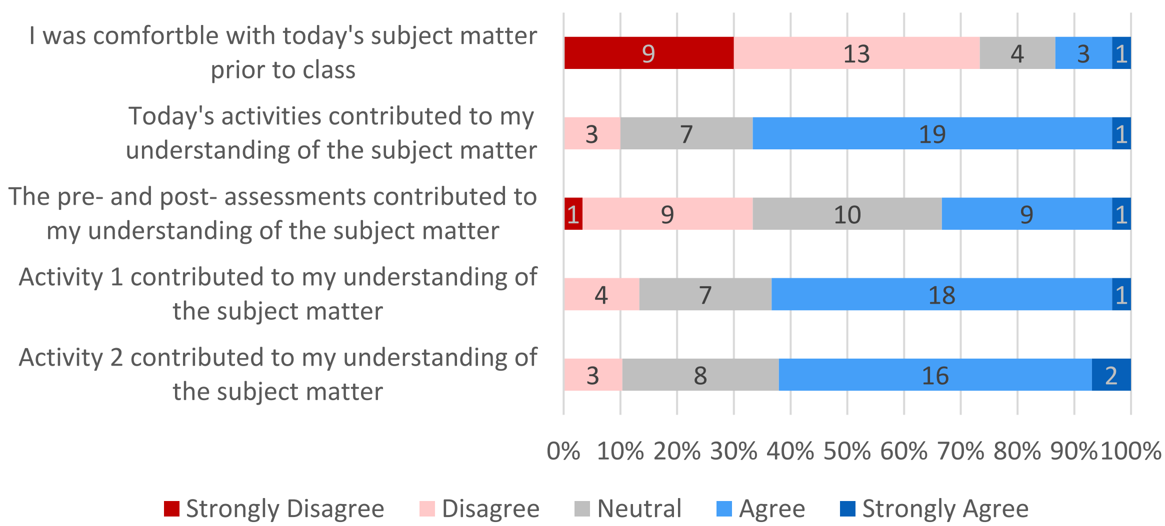


Figure 34: Fall 2019 Beam Deflection module Post-Module survey responses by frequency

5.2.1.4. <u>Module Perception Survey Results</u>

The module perception survey was distributed only in the Torsion Module. This survey was deemed necessary to help understand factors that may have had an impact on the students' performance on the modules. For Torsion, the module perception for the students' role is broken down in Figure 35. For the student's role, over 60% of students saw the value of working with the 3D apparatus and over 80% of students saw the value in working with groups. The students did not believe the time used for the activities was beneficial. This was due to the time allotted for the class being cut down to 50-minutes instead of the 75-minute class the modules were planned for.

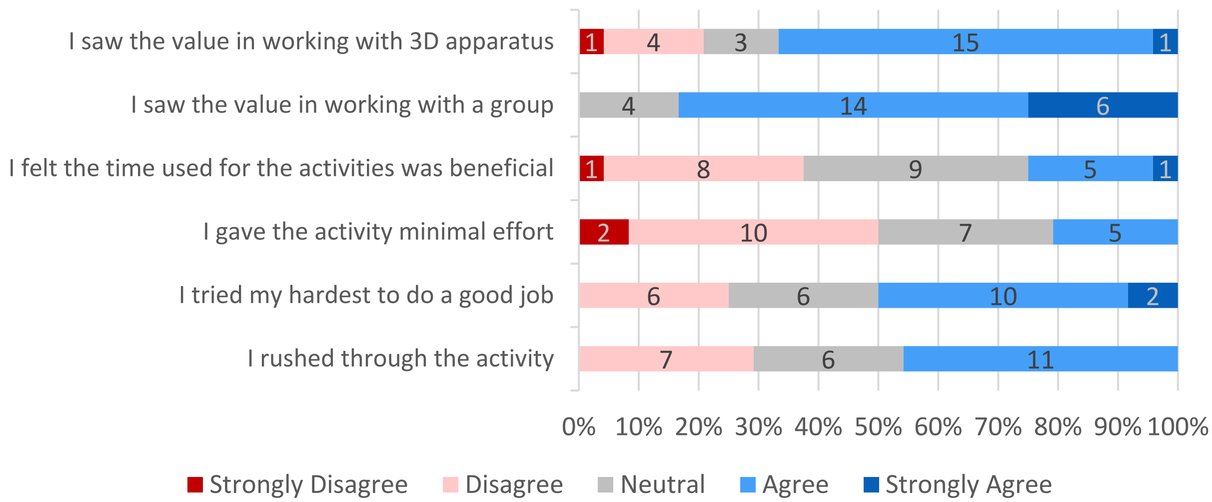


Figure 35: Fall 2019 Torsion Module Perception survey responses by frequency

For the instructor role portion of the module perception survey (Figure 36), the students' responses were distributed evenly across the scale. The data shows that 50% of the students believed the instructors explained the purpose of the activities and explained what was expected of them. Most of the students either has a neutral stance or did not believe the activities used were of the right difficulty level. This shows that there is room for improvement with the types of questions used in these modules.

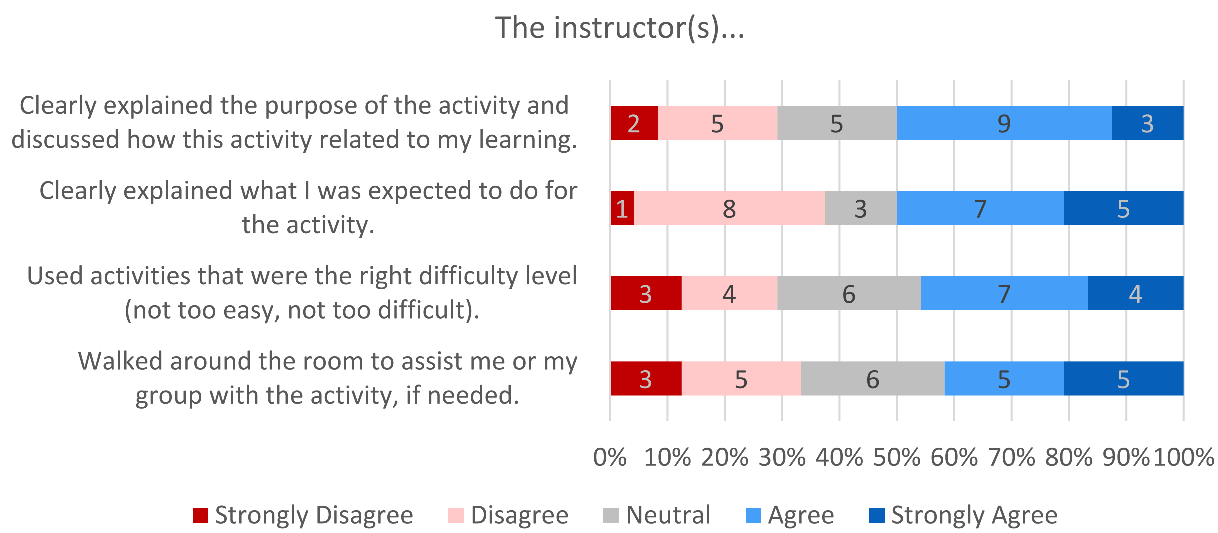


Figure 36: Fall 2019 Torsion Module Perception survey responses by frequency pertaining to the instructor(s) role in the module

5.2.1.5. <u>Post-Exam Survey Results</u>

The Post-Exam survey was distributed after the first exam to understand how the modules impacted the students' ability to complete the course deliverables. The students were asked to rate how much each of the two modules helped in preparing for the assignments and exams. *Figure 37* breaks down the frequency of responses for the survey. For the Stress and Strain module, 25% of the students believed the activities did not help them at all, and 66% of students believed the activities helped them a little bit. Similarly, 23% of students did not believe the Axial Loading activities contributed to their ability to complete the class deliverables. Less than 10% of respondents believed that the modules impacted their ability to do the deliverables a lot.

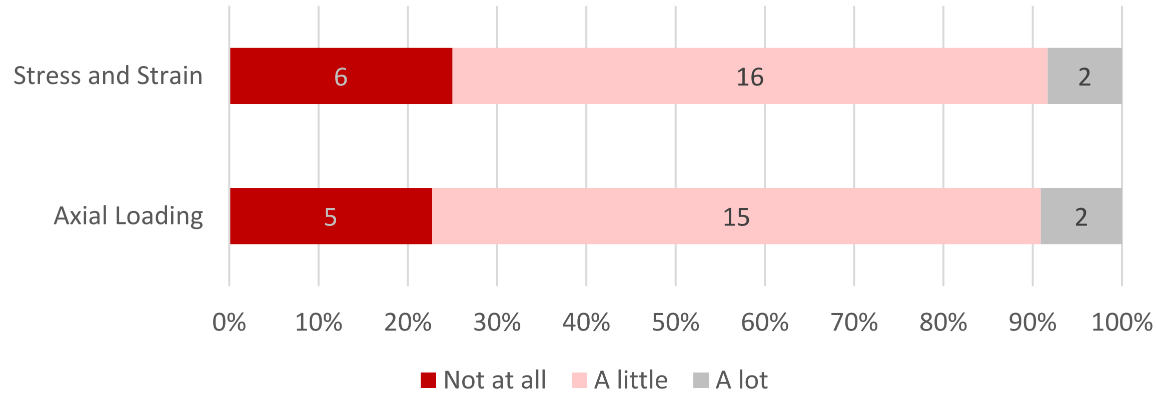


***Figure 37*: Fall 2019 Post-Exam Survey responses by frequency about how the activities helped the student on their class deliverables.**

In the future deployments of this survey, the response scale was changed to a 5-point Likert-scale from Strongly Disagree to Strongly Agree. This was seen as more beneficial to help understand the magnitude that the modules assisted the students in preparing for their course deliverables.

5.2.2. Spring 2020

5.2.2.1. Learning and Instruction Survey Results

The Learning and Instruction survey allowed for the research team to understand the type of students there were in the Spring 2020 participant pool. Figure 38 shows the distribution of the students' answers. Similar to the Fall 2019 Learning and Instruction Survey results, about 80% of students wanted to listen to the instructor lecture during class, and 90% of students wanted to watch the instructor demonstrate how to solve problems in every class. Over 60% of students wanted to solve problems in a group during class, either every class or once a week. Roughly 35% of the students want to make and justify assumptions when not enough information is provided and solve problems that have more than one correct answer once a week in an ideal class. This shows that the students of Spring 2020 wanted to use their critical thinking skills to solve ambiguous problems, also. Unlike Fall 2019 and doing hands on activities during class, 24% of the Spring 2020 students would like to do the activities in every class and 30% of students wanted to do hands-on activities once a week. Comparatively, this shows that the Spring 2020 class of students were more willing to work on alternative activities to traditional lecture styles more frequently. Also, over 60% of the students would want to solve problems in a group during class, either in every class or once a week.

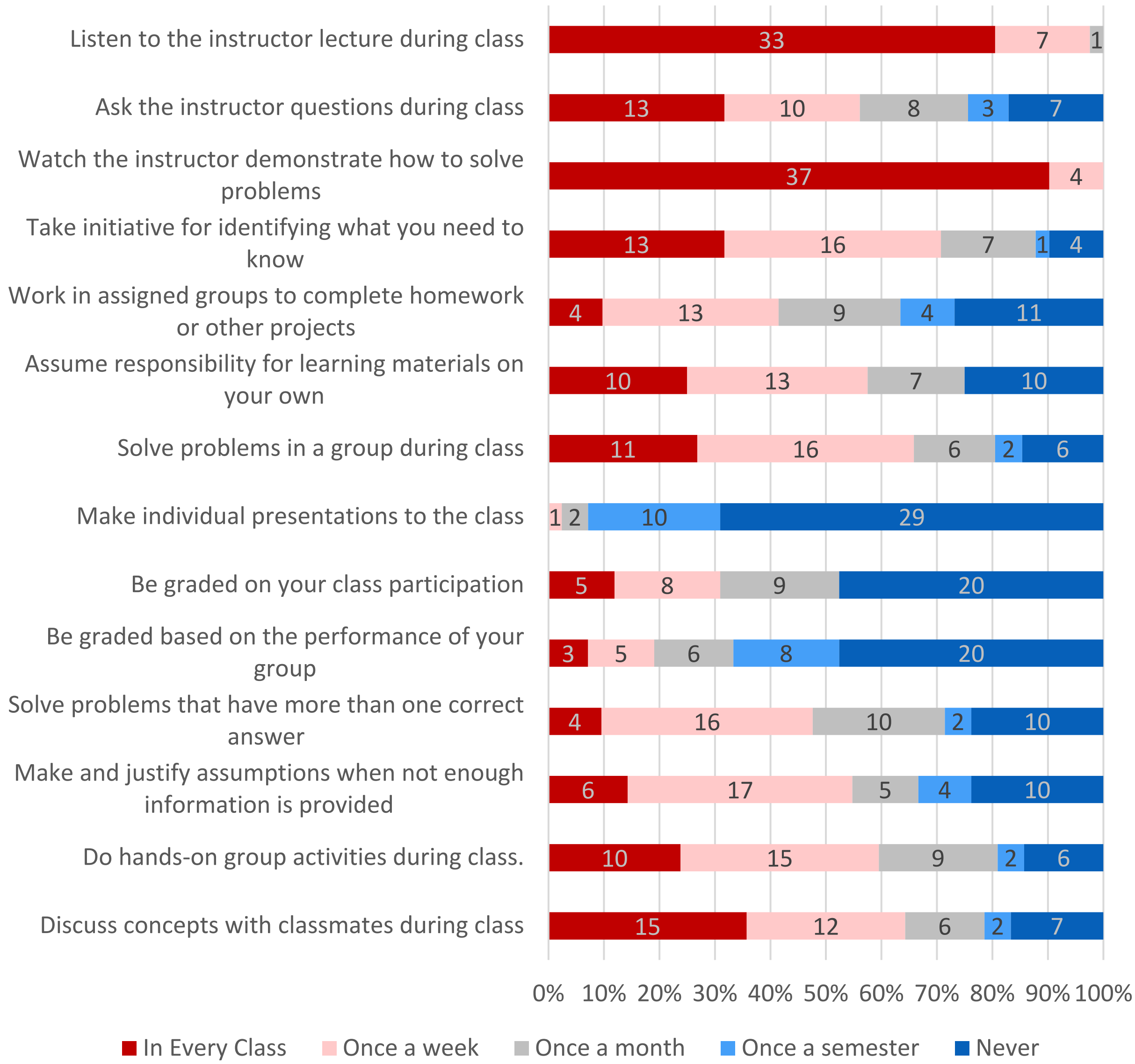


Figure 38: Spring 2020 Learning and Instruction survey responses by frequency

5.2.2.2. Self-Efficacy Survey Results

In Spring 2020, the intervention structure no longer included a quiz-like assessment – it now featured self-efficacy surveys geared to understanding the students self-reported confidence. The averages of the scores were computed for each self-efficacy task before and after the intervention activities were given.

5.2.2.2.1. Axial Loading Module

Figure 39 shows the comparison of averages for all nine tasks asked of the students. All tasks had a difference in the pre- and post-assessment responses; tasks 2, 7, and 8 have the least difference in their averages (<0.5). The most distinct changes in average occurred between the tasks 1 and 9, which were greater than 1.

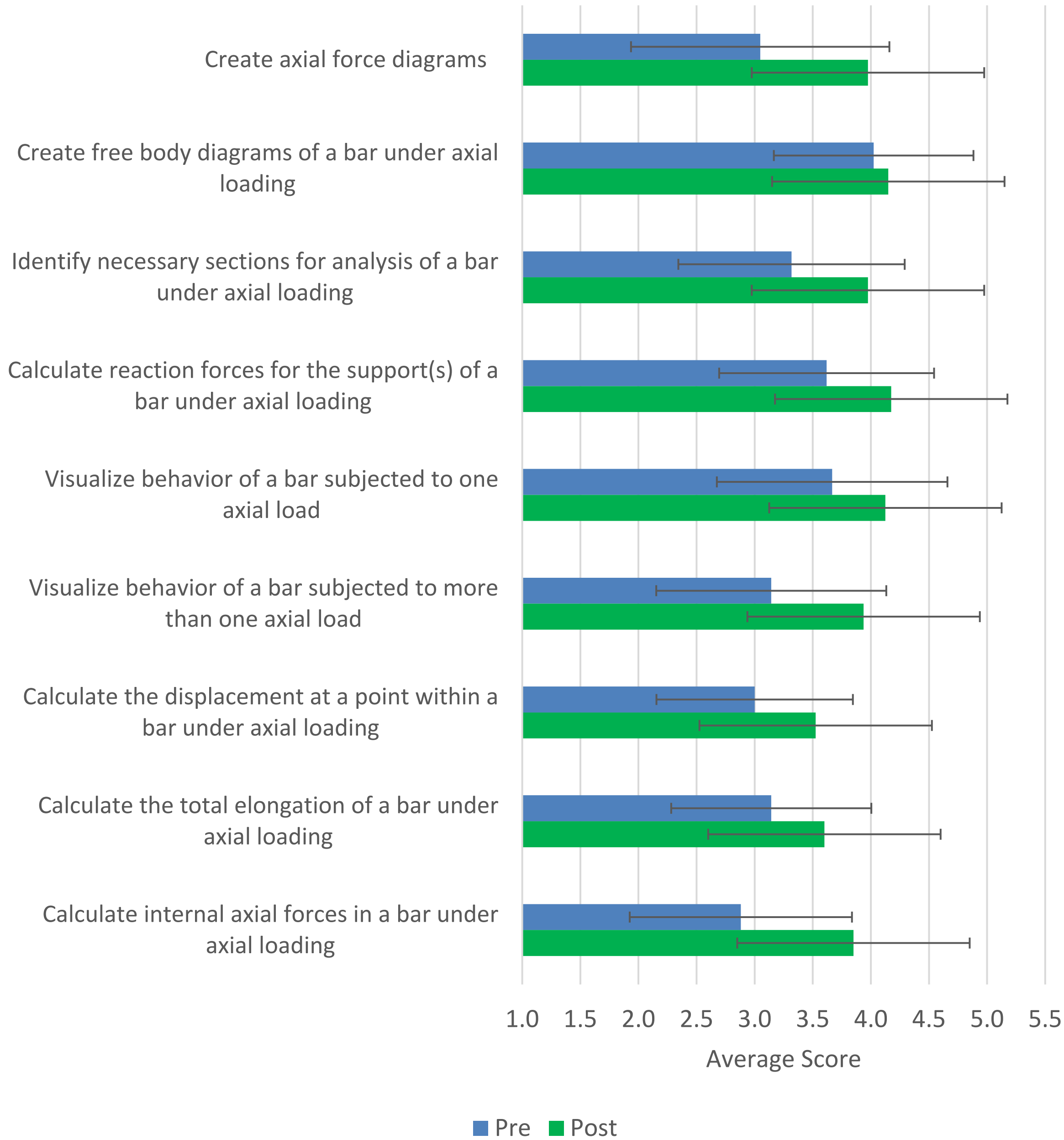


Figure 39: Spring 2020 Self-Efficacy survey response averages for the nine Axial Loading module tasks; Error bars show ± one standard deviation

A Sign test was used to understand if there was a significance of the total groups' change in self-efficacy before and after the interventions. The hypothesis is there is a difference between the pre-intervention and post-intervention self-efficacy scores of the students for the Axial Loading module. The self-efficacy data set meets the Sign test's assumption of the data being ordinal, matched pairs, and not normally distributed or symmetric. The Sign test (Table 14) reveals that the intervention activities did elicit a significant statistical ($p < 0.05$) change for all self-efficacy tasks except task 2 ($p = 0.286$), which is "Create free body diagrams of a bar under axial loading". It can be concluded that the module activities did elicit a change in the self-reported self-efficacy to complete the majority of the outlined tasks.

Table 14: Spring 2020 Axial Loading Self-Efficacy statistical analysis results from Sign test

Task		Ranks (n)			Test Statistics	
		Positive	Negative	Ties	Z	p
1.	Create axial force diagrams	26	3	11	-4.085	0.000**
2.	Create free body diagrams of a bar under axial loading	14	8	18		0.286
3.	Identify necessary sections for analysis of a bar under axial loading	21	4	14		0.001**
4.	Calculate reaction forces for the support(s) of a bar under axial loading	19	2	19		0.000**
5.	Visualize behavior of a bar subjected to one axial load	17	5	18		0.017*
6.	Visualize behavior of a bar subjected to more than one axial load	24	3	13	-3.849	0.000**
7.	Calculate the displacement at a point within a bar under axial loading	17	3	20		0.003*
8.	Calculate the total elongation of a bar under axial loading	17	4	19		0.007*
9.	Calculate internal axial forces in a bar under axial loading	24	2	14	-4.118	0.000**

*significant ($p<0.05$);** highly significant ($p<0.001$); blanks in *Z* column means binomial distribution was used

5.2.2.2.2. Torsion Module

The Self-Efficacy survey for the Torsion module had 14 tasks that were asked of the students. All of the task averages (Figure 40) from the pre and post surveys has at least a 0.5 point jump, except Task 10 and Task 12. Task 10 asked the students to rate their confidence in calculating reaction forces of a statically indeterminate bar in torsion. Task 12 asked their confidence to calculate the max shear stress of a bar in torsion. These possibly have the lowest difference between averages because the Torsion problem was a statically indeterminate beam, and the students were not able to finish the module to the point of the answers. There were videos uploaded to YouTube to help the students understand the solution to the problem after the module was deployed.

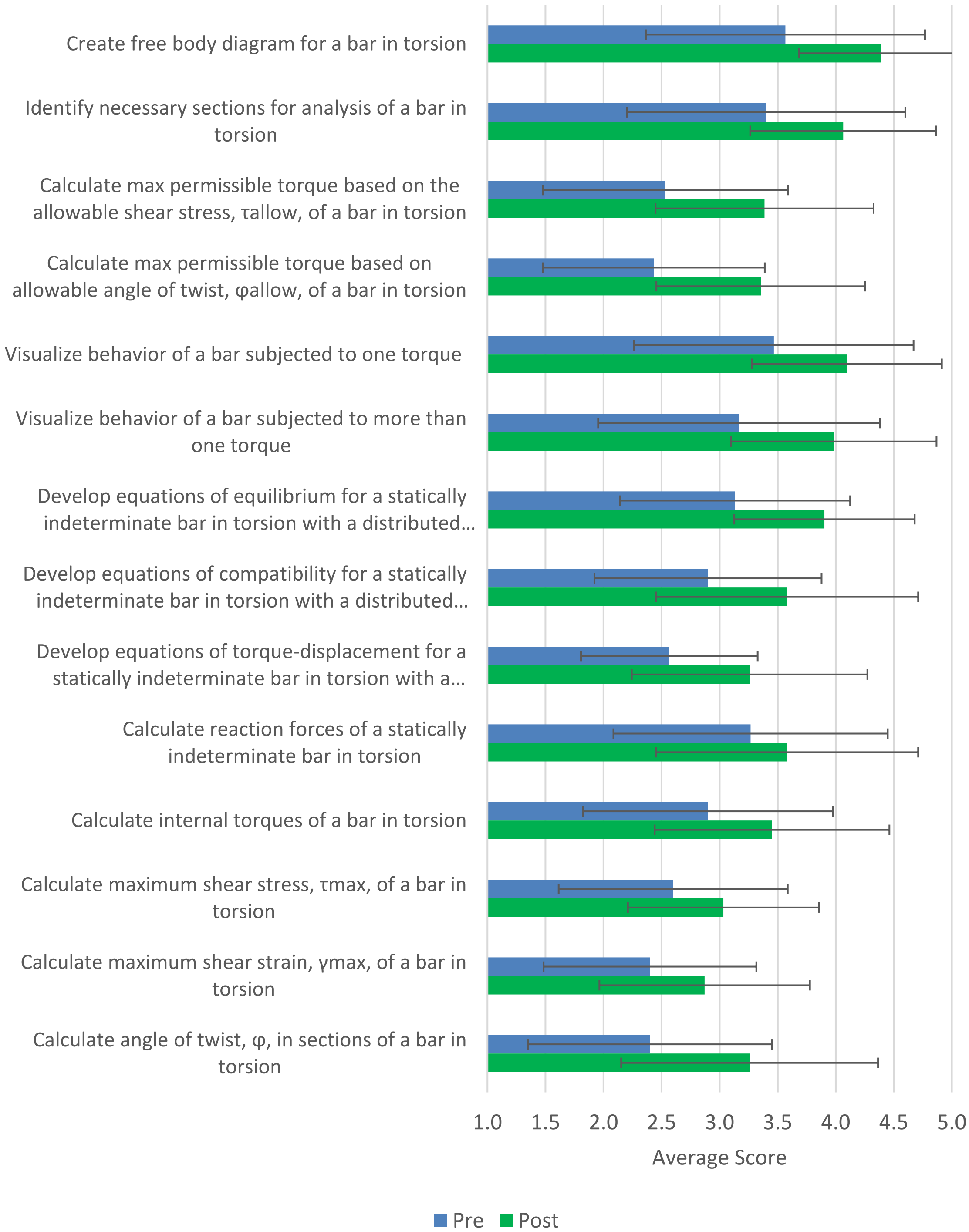


Figure 40: Spring 2020 Self-Efficacy survey response averages for the 14 Torsion module tasks; Error bars show ± one standard deviation

A Sign test was used to understand if there was significance in the total groups' change in self-efficacy before and after the interventions. The hypothesis is there is a difference between the pre-intervention and post-intervention self-efficacy scores of the students for the Torsion module. The Self-Efficacy data set meets the Sign test's assumptions of the data being ordinal, matched pairs, and not normally distributed or symmetric. The Sign test showed that the intervention activities did elicit a significant statistical ($p < 0.05$) change for all self-efficacy tasks except Task 10 ($p = 0.481$) and Task 12 ($p = 0.118$). As noted earlier, Tasks 10 and 12 possibly had no significance in the difference between the change from pre- and post-module due to the length of the problem given in this module and the advanced nature of the Activity 2 problem.

Table 15: Spring 2020 Torsion Self-Efficacy statistical analysis results from Sign test

	Task	**Ranks (n)**			**Test Statistics**
		Positive	Negative	Ties	*p*
1.	Create free body diagram for a bar in torsion	11	1	14	0.006*
2.	Identify necessary sections for analysis of a bar in torsion	14	3	9	0.013*
3.	Calculate max permissible torque based on the allowable shear stress, a_{llow}, of a bar in torsion	15	2	9	0.002*
4.	Calculate max permissible torque based on allowable angle of twist, ϕ_{allow}, of a bar in torsion	15	2	9	0.002*
5.	Visualize behavior of a bar subjected to one torque	11	0	15	0.001*
6.	Visualize behavior of a bar subjected to more than one torque	16	1	9	0.000**
7.	Develop equations of equilibrium for a statically indeterminate bar in torsion with a distributed load	18	0	8	0.000**
8.	Develop equations of compatibility for a statically indeterminate bar in torsion with a distributed load	15	2	9	0.002*
9.	Develop equations of torque-displacement for a statically indeterminate bar in torsion with a distributed load	13	2	11	0.007*
10.	Calculate reaction forces of a statically indeterminate bar in torsion	11	7	8	0.481
11.	Calculate internal torques of a bar in torsion	14	4	8	0.031*
12.	Calculate maximum shear stress, τ_{max}, of a bar in torsion	11	4	11	0.118
13.	Calculate maximum shear strain, γ_{max}, of a bar in torsion	12	3	11	0.035*

14.	Calculate angle of twist, ϕ, in sections of a bar in torsion	13	1	12	0.002*

*significant (p<0.05); ** highly significant (p<0.001)

Self-Efficacy has been shown, in this study, effective in helping portray the students' ability to tackle the steps to solve complex problems in the selected topics. Although formative and summative scores have been used to assess the impact the modules had on the students, those scores are subjective in nature based on who is grading them. These self-reported metrics give a first-hand insight into how the students believe the interventions have enhanced their knowledgebase.

5.2.2.3. Module Perception Survey Results

The Module Perception Survey was distributed in the Axial Loading and Torsion modules. For both module deployments, over 50% of students saw the value of the 3D apparatus and over 65% saw the value of working in groups. These two being the pillar of what the activities were developed for, these results show that the students were receptive to this Intervention 3 structure of the module and its components: a challenging problem and an accompanying 3D apparatus.

The students perceived the role of the professor in a positive way. Most students believed the expectations and purpose of the activities were clearly explained by the instructor(s). They also believed the activities used were of the right difficulty level. These results aligned with the goal of developing activities that were of consistent difficulty with those problems the students would be exposed to in the course.

5.2.2.3.1. Axial Loading Module

For the Axial Loading module, 55% of the students saw the value of working with the 3D apparatus. Furthermore, 73% of students reported they saw the value of group learning with the activity and felt the time used for the activities was beneficial. Also, the 67% of students tried to do their hardest on the module, while 25% of students gave minimal effort. Figure 41 shows the frequency of the Module Perception responses.

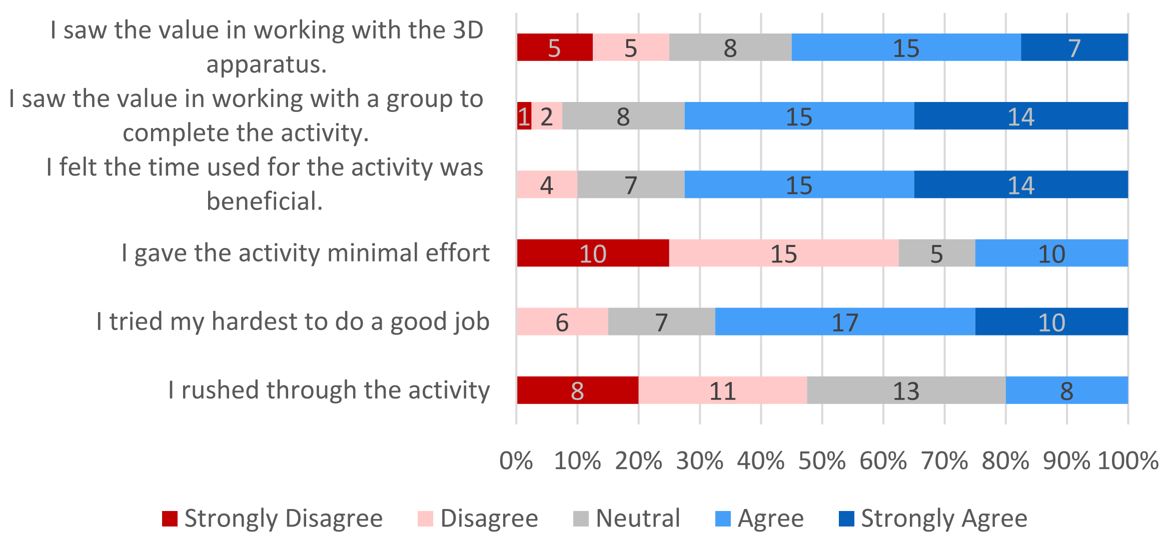


Figure 41: Spring 2020 Axial Loading Module Perception survey responses by frequency

In this module, 76% of the students agreed the instructor(s) explained the purpose of the activity and what was expected for them to do for the activity. Over 80% of these students believed the activities were the right difficulty level. Amazingly, 68% of the students strongly agreed and 26% agreed the research team walked around to assist. This reflects the goal, which was the reduce the ambiguity of the activities so the students could benefit more from it. Lastly, 82% of the students believed the activities were of the right difficulty level. Figure 42 shows the frequency of responses for the instructor(s) role.

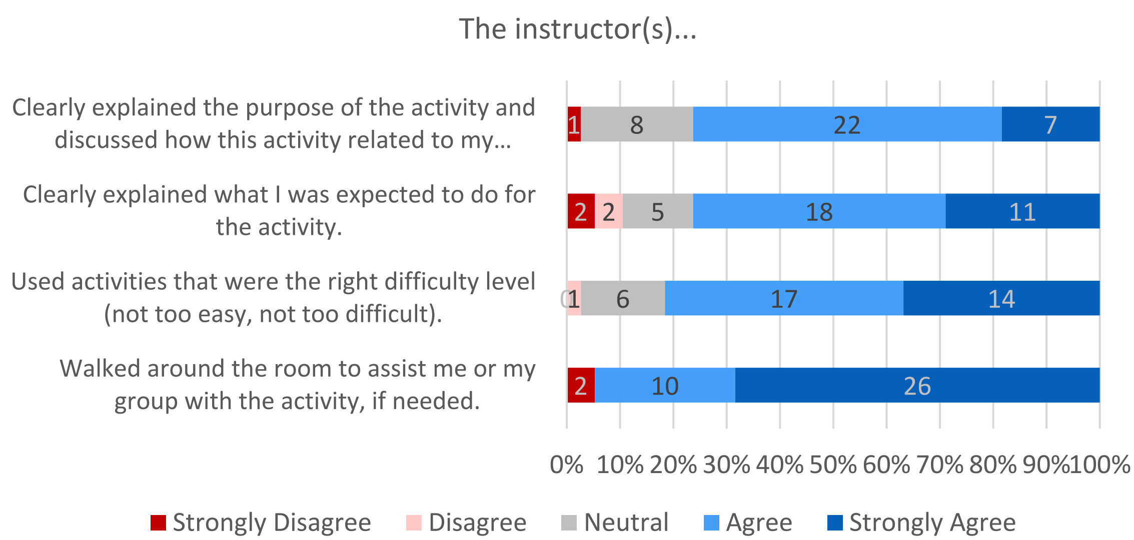


Figure 42: Spring 2020 Axial Loading Module Perception survey responses by frequency pertaining to the instructor(s) role in the module

5.2.2.3.2. Torsion Module

Similarly with the Axial Loading module perception survey results, 58% of the students saw value in working with the 3D apparatus. Figure 43 shows that there was great acceptance, and the students believed that the 3D model helped them understand the information. Of the 31 students present, 65% of students saw the value of working in groups, and 55% of students felt the time used for the activity was beneficial.

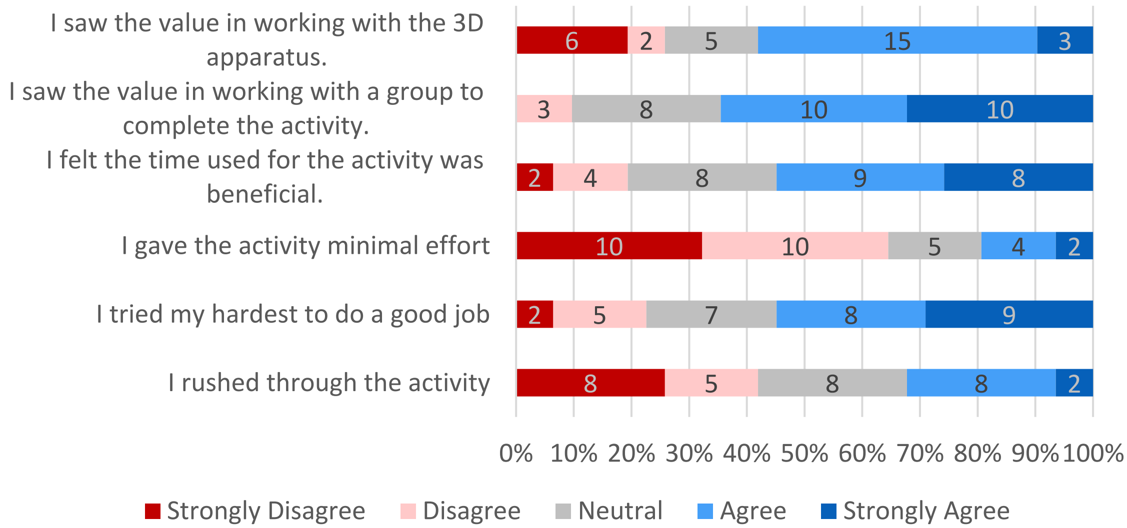


Figure 43: Spring 2020 Torsion Module Perception survey responses by frequency

For the instructor's role in the module, 68% of students believed the purpose of the activity was clearly explained, and 87% of the students believed it was clearly explained what that expected of them or the activities. Similar to Axial Loading, the majority of students (81%) agreed the instructors walked around and helped. Plus, 79% of the students believed the activities were of the right difficulty level. Compared to the Fall 2019 semester Torsion module, where 46% of students believed the activity levels were of the right difficulty level, this semester drastically increased that proportion. Figure 44 shows the breakdown of students' responses.

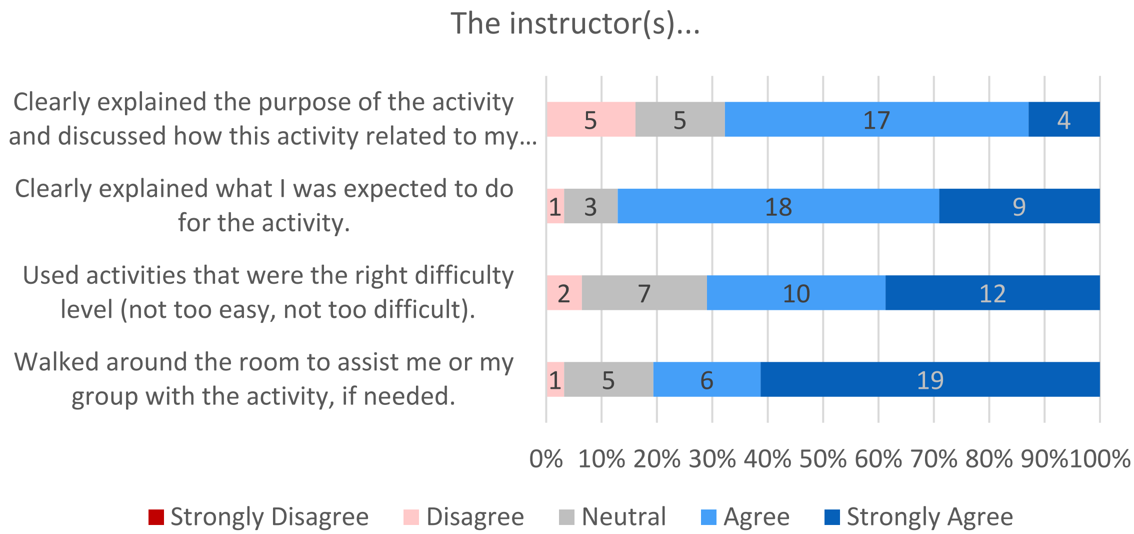


Figure 44: Spring 2020 Torsion Module Perception survey responses by frequency pertaining to the instructor(s) role in the module

5.2.2.4. Post-Exam Survey Results

The post-exam survey was distributed in the beginning of the Torsion module because of its inquiry about how the Axial Loading module helped prepare the students for the course deliverables. Figure 45 shows the distribution of answers for the survey. This chart shows 68.97% of the students agreed or strongly agreed that the module activities prepared them for the homework assignments, while 58.62% of students believed the activities prepared then for the Exam. It can be concluded that the Axial Loading module helped the students prepare for the homework and exams. Less than 14% of the students disagreed or strongly disagreed that the module helped with their efforts on the class deliverables.

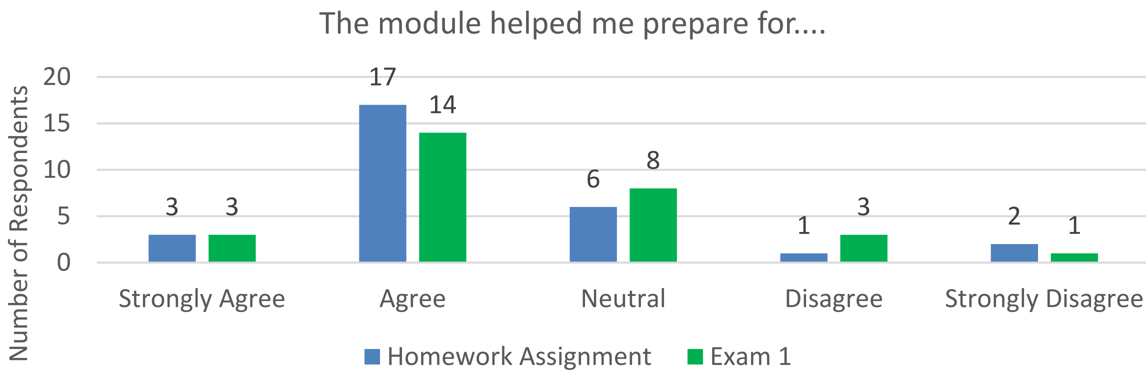


Figure 45: Spring 2020 Post-Exam survey responses by frequency

5.2.2.5. Post-Module Survey Correlation

Kendall's Tau-b correlation was run to determine the relationship between course deliverable scores by students and the Post-Module survey, and the relationship between the student's responses to the Post-Module survey and the change in reported Self-Efficacy amongst 40 students. The assumptions the data met were that it is ordinal or continuous, and there is a monotonic relationship between the pairs of data. Kendall's Tau-b is less susceptible to errors than Spearman rank order's coefficient and is more effective in analyzing smaller sample sizes.

5.2.2.5.1. Axial Loading Module

For the Axial Loading module, the hypothesis is there is a relationship between the Axial Loading homework scores and Exam 1 scores and the Post-Module survey responses. Unfortunately, the homework grades and Post-Module survey statements had no statistically significant correlation. Based on the results of the study, significant correlation between the Exam 1 score and "Today's activities contributed to my understanding of the subject matter" ($\tau_b = -0.341$, $p = 0.008$) and "Activity 2 contributed to my understanding of the subject matter" (τ_b = -0.321, p = 0.013) were made. The higher the exam score, the lower the rating of the post-exam score statements. These results go against the hypothesis of students who are exposed to intervention activities will have higher course deliverable scores in that topic. The correlation is negative for the students who responded with higher agreement that the activity impacted their understanding for the better.

Kendall's Tau-b correlation was run to understand the relationship between the Post-Module survey and Self-Efficacy survey. The hypothesis is there is a positive relationship between the Axial Loading Post-Module survey responses and the difference in the Self-Efficacy scores. There were five strong, positive correlations that were statistically significant. There was a statistically significant correlation between "Today's activities contributed to my understanding of the subject matter" and their self-reported ability to create free body diagrams of a bar under axial loading (τ_b = 0.322, p = 0.024) and calculate internal axial forces in a bar under axial loading (τ_b = 0.362, p = 0.011). There was a statistically significant correlation between Activity 2 contributing to the students' understanding of the subject matter and their ability to create free body diagrams of a bar under axial loading (τ_b = 0.344, p = 0.016). The statement "After having gone through the activity, my knowledge of the topic has improved" had two statistically significant correlations between the students' ability to calculate the total elongation of a bar under axial loading (τ_b = 0.380, p = 0.009) and calculate internal axial forces in a bar under axial loading (τ_b = 0.446, p = 0.002).

5.2.2.5.2. Torsion Module

For the Torsion module, the hypothesis is there is a relationship between the Torsion homework scores and Exam 2 scores and the Post-Module survey responses. There were no statistically significant correlations between the homework grades and Post-Module survey statements. For the Exam 2 scores, there was a statistically significant negative correlation with the Exam 2 score and responses to the statement "I was comfortable with today's subject matter prior to class" (τ_b = -0.299, p = 0.035). This correlation shows that those who believed they were not very comfortable with the subject matter prior to the activities had higher exam scores. The results show that the activities may have helped with their confidence, whether they understood Torsion enough to do well on the exams.

Kendall's Tau-b correlation was run to understand if there was a relationship between the students' change in Self-Efficacy survey and their Post-Module survey responses. The hypothesis is there is a positive relationship between the Torsion Post-Module survey responses and the difference in the Self-Efficacy scores. There were eight strong, positive correlations that were statistically significant. There was a statistically significant correlation between the student's responses to "Today's activities contributed to my understanding of the subject matter" and their self-reported ability to calculate reaction forces of a statistically indeterminate bar in torsion (τ_b = 0.346, p = 0.022). There was a statistically significant correlation between Activity 1 contributing to the students' understanding of the subject matter and their ability to visualize behavior of a bar subjected to one torque (τ_b = 0.402, p = 0.010). There was a statistically significant correlation between Activity 2 contributing to the students' understanding of the subject matter and their ability to calculate reaction forces of a statically indeterminate bar in torsion (τ_b = 0.330, p = 0.027). Lastly, the statement "After having gone through the activity, my knowledge of the topic has improved" had two strong, positive correlations that were statistically significant: calculate reaction forces of a statically indeterminate bar in torsion (τ_b = 0.370, p = 0.014) and calculate internal torques of a bar in torsion (τ_b = 0.302, p = 0.045).

Based on these correlations, it can be concluded that the students believed the Activities had an impact on their knowledgebase, and their self-reported abilities follow that trend.

5.2.2.6. Module Perception Survey Correlation

Kendall's tau-b was used to determine the relationship between the class deliverables and the students' responses to the module perception survey statements, and to determine the relationship between the student's responses to the Module Perception survey and the difference in reported self-efficacy. The assumptions the data met were that it is ordinal or continuous, and there is a monotonic relationship between the pairs of data

5.2.2.6.1. Axial Loading Module

For Axial Loading, the hypothesis is there is a positive relationship between the Axial Loading Module Perception survey statements and the Axial Loading homework and Exam 1. Kendall's Tau-b determined the Module Perception survey and class deliverables had two positive, significant correlations to the Axial Loading homework in relation to the student's role portion of the survey and one regarding the instructor's role portion of the survey. Based on the results of the study, there was a strong positive correlation between the Axial Loading homework and "I saw the value in working with a group to complete the activity" (τ_b = 0.279, p = 0.038) and "I felt the time used for the activity was beneficial" (τ_b = 0.271, p = 0.044), which were statistically significant. There was also a strong, positive correlation between the homework and the students agreeing "The instructor(s) used activities that were the right difficulty level" (τ_b = 0.338, p = 0.016), which was statistically significant. These results show that the students' opinion of group work and time used for the activities are proportional to the homework scores. Also, the activities being the right difficulty level was beneficial to completing the homework and obtaining a higher score.

For Axial Loading, the hypothesis is there is a positive relationship between the Axial Loading Module Perception survey statements and the students' change in self-efficacy. Kendall's Tau-b correlation revealed three strong, positive correlations between the students' change in self efficacy and the perception of the module. There was a strong positive correlation between the students responding, "I saw the value in working with a group to complete the activity" and their ability to calculate reaction forces for the supports of a bar under axial loading(τ_b = 0.295, p = 0.037). There are correlations between the students' response to "The instructor(s) clearly explained the purpose of the activity and discussed how this activity related to my learning" and the students' ability to create axial force diagrams (τ_b = -0.289, p = 0.045) and the students' ability to calculate the displacement at a point within a bar under axial loading (τ_b = 0.319, p = 0.031). These results show that there is possibly a relationship between the instructor's role in the module and the students' self-perceived ability to do some axial loading calculations.

5.2.2.6.2. Torsion Module

For the Torsion module, the hypothesis is there is a positive relationship between the Torsion Module Perception survey statements and the Torsion homework and Exam 2 scores. Kendall's Tau-b test did not yield any statistically significant correlations between the Module Perception survey and the Torsion Homework and Exam 2 scores.

For the Torsion module, the hypothesis is there is a positive relationship between the Torsion Module Perception survey statements and the students' change in self-efficacy. Kendall's Tau-b correlation revealed three strong statistically significant correlations for the students' responses to the module perception survey and the students' self-reported abilities. A strong, negative correlation was found between the students saying, "I rushed through the activity" and their ability to calculate maximum shear strain of a bar in torsion (τ_b = -0.312, p = 0.036). There was a strong, positive correlation between the students' response to "The instructor(s) clearly explained the purpose of the activity and discussed how this activity related to my learning" and their self-reported ability to develop equations of compatibility for a statically indeterminate bar in torsion with a distributed load (τ_b = 0.326, p = 0.029). Lastly, there was a strong, positive correlation between the students' response to "The instructor(s) used activities that were the right difficulty level (not too easy, not too difficult)" and their self-reported ability to calculate reaction forces of a statically indeterminate bar in torsion (τ_b = 0.382, p = 0.012).

5.2.3. Fall 2020

In Fall 2020, the modules were deployed in the Intervention 4 Structure. This consisted of one activity virtually in breakout groups on BlueJeans. This semester, there were virtual deployment problems and the semester ended with less students being retained for the overall course during the class time; therefore, there were few students willing to participate in the virtual module deployments. In the beginning of the semester, the Axial Loading module and the Torsion modules were deployed with more than 10 students participating. Towards the end of the semester, Combined Loading and Beam deflection were deployed, and there were less than 10 students who stayed for the whole class time. Due to this, the Axial Loading and Torsion module survey results were examined and correlated, while the Combined Loading and module surveys were assessed. The Beam Deflection post-survey results are not reported here due to only one student participating.

5.2.3.1. Learning and Instruction Survey Results

When the learning and instruction survey was distributed, there were 36 students present to participate in the virtual study. Figure 46 shows the distribution of the students' answers. Similar to the Fall 2019 and Spring 2020 Learning and Instruction Survey results, about 80% of students wanted to listen to the instructor lecture during class, in every class, and 20% wanted to listen to the instructor during class at least once a week. 80% of students wanted to watch the instructor demonstrate how to solve problems in every class. About 58% of students wanted to solve problems in a group during class, either every class or once a week. Roughly 50% of the students want to make and justify assumptions when not enough information is provided and solve problems that have more than one correct answer, once a week in an ideal class. This shows that the students of Spring 2020 wanted to use their critical thinking skills to solve ambiguous problems, also. Although a virtual environment, in an ideal class 58% of students would want to do hands-on activities during class, either in every class or once a week. Comparatively, this shows that the Fall 2020 class of students were as willing to work on alternative activities to traditional lecture styles more frequently. Also, over 60% of the students would want to solve problems in a group during class, either in every class or once a week.

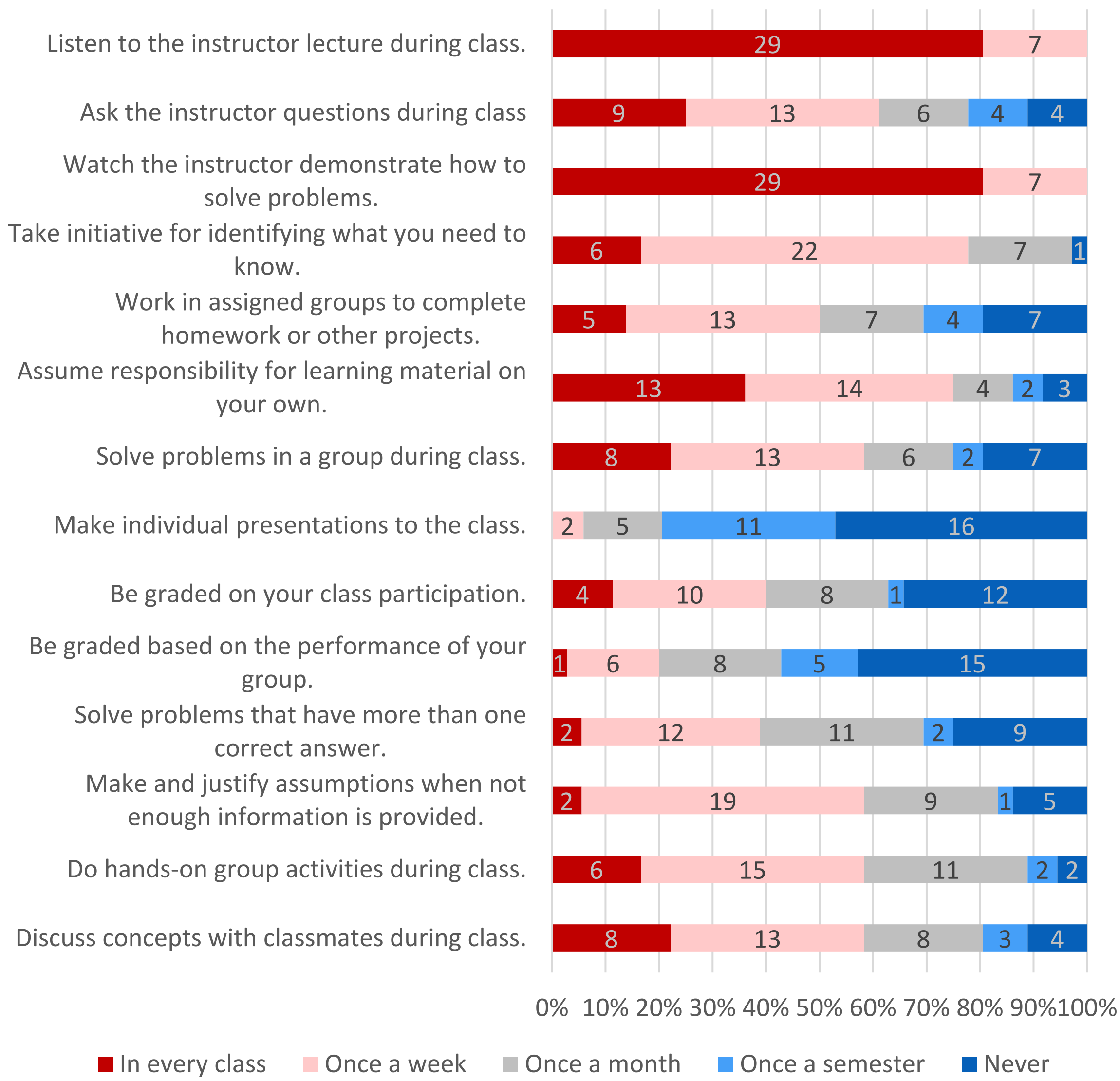


Figure 46: Fall 2020 Learning and Instruction survey responses by frequency

5.2.3.2. <u>Self-Efficacy Survey Results</u>

5.2.3.2.1. Axial Loading Module

The Self-Efficacy survey for the Axial Loading module had 14 tasks that were asked of the students. All the task averages from the pre and post surveys has at least a 0.5 point jump. These results (Figure 23) reveal that the students possibly believed the active learning module helped with their abilities to complete these tasks. This module was unique in this semester because the students were able to experience Activity 1 and Activity 2, like in Intervention 3, but in virtual breakout rooms. This was later changed to only a sole activity for the Torsion and later modules in the semester. It is possible that the first group activity did have a substantial impact on the students combined with Activity 2.

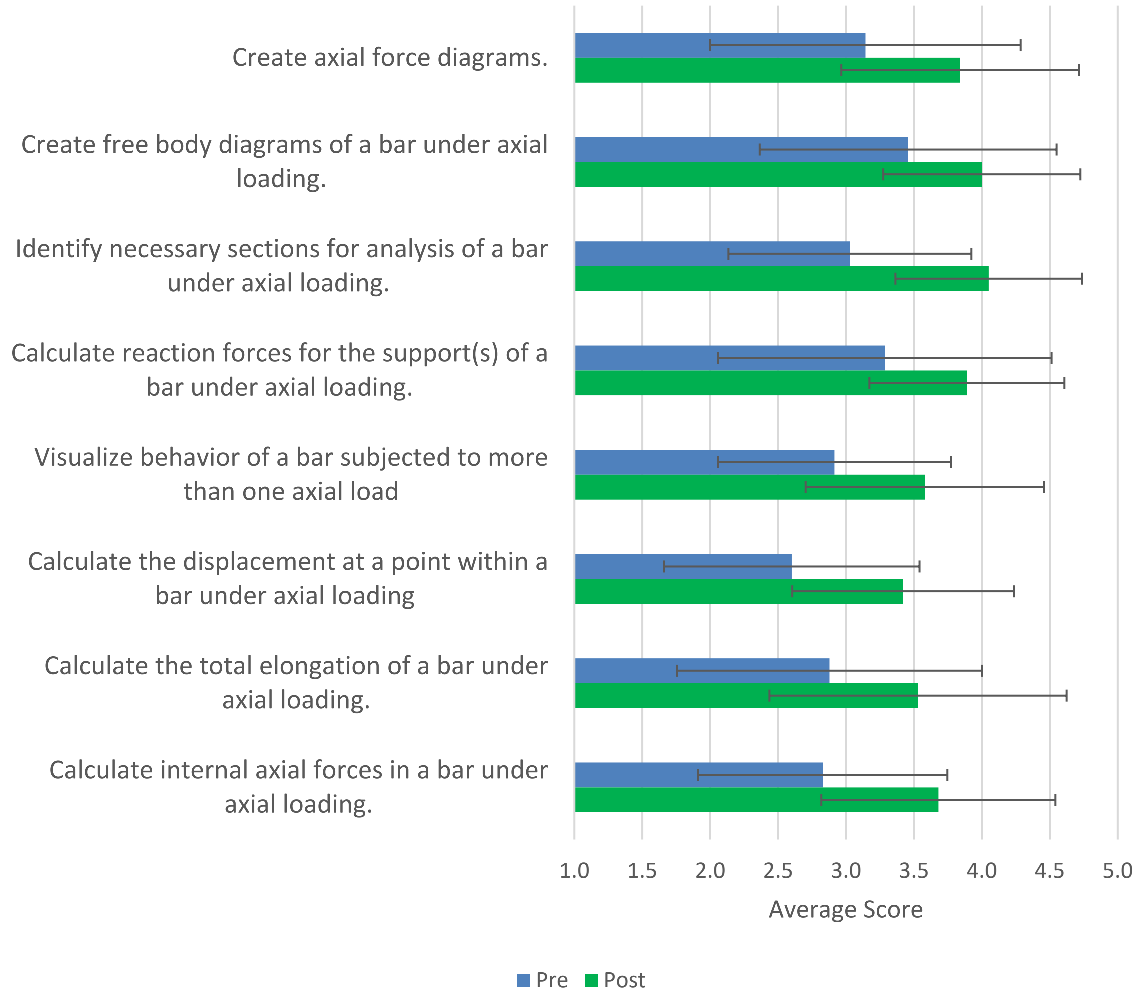


Figure 47: Fall 2020 Self-Efficacy survey response averages for the eight Axial Loading module tasks; Error bars show ± one standard deviation

A Sign test was used to understand if there was a significance of the total groups' change in self-efficacy before and after the interventions. The Self-Efficacy data set meets the Sign test's assumption of being ordinal, matched pairs, and not normally distributed or symmetric. The Sign test (Table 16) reveals that the intervention activities did elicit a significant statistical (p < 0.05) change for all self-efficacy tasks using binomial distribution. It can be concluded that the module activities did elicit a change in the self-reported self-efficacy to complete the outlined tasks.

Table 16: Fall 2020 Axial Loading Self-Efficacy statistical analysis results from Sign test

	Task	Ranks (n)			Test Statistics
		Positive	Negative	Ties	p
1.	Create axial force diagrams	10	1	8	0.012*
2.	Create free body diagrams of a bar under axial loading	11	0	8	0.001**
3.	Identify necessary sections for analysis of a bar under axial loading	12	1	6	0.003*
4.	Calculate reaction forces for the support(s) of a bar under axial loading	8	1	10	0.021*
5.	Visualize behavior of a bar subjected to more than one axial load	9	1	9	0.039*
6.	Calculate the displacement at a point within a bar under axial loading	12	1	7	0.021*
7.	Calculate the total elongation of a bar under axial loading	10	2	7	0.039*
8.	Calculate internal axial forces in a bar under axial loading	14	2	3	0.004*

*significant ($p<0.05$);** highly significant ($p<0.001$)

5.2.3.2.2. Torsion Module

The Self-Efficacy survey for the Torsion module had 13 tasks that were asked of the students. All the task averages (Figure 24) from the pre and post surveys had at least a 0.5 point jump, except Task 4, Task 11, and Task 12. Task 10 asked the students to rate their confidence in calculating the max torque based on the angle of twist of a bar in torsion. Task 11 asked their confidence to calculate the max shear stress of a bar in torsion. Task 12 asked their confidence to calculate the max shear strain of a bar in torsion. These possibly have the lowest difference between averages because the Torsion problem was a statically indeterminate beam, similar to Spring 2020, and the class was not able to finish the module. Due to the time constraints, the answers were not able to be fully explained nor were the students able to ask questions. Due to these circumstances, there were videos posted on the modules that explained the solutions to the problem.

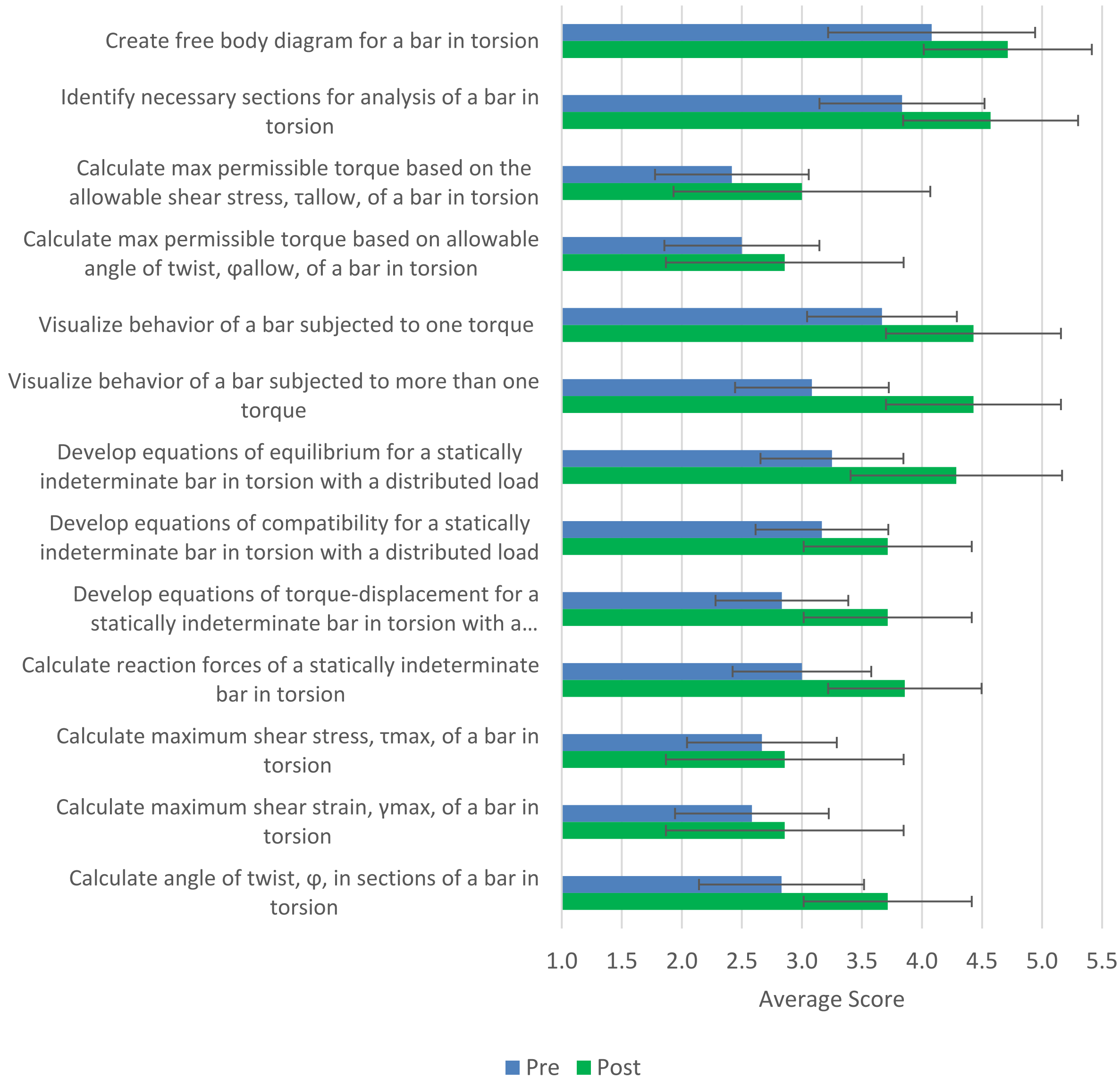


Figure 48: Fall 2020 Self-Efficacy survey response averages for the 13 Torsion module tasks; Error bars show ± one standard deviation

A Sign test was used to understand if there was a significance of the total groups' change in self-efficacy before and after the interventions. The Self-Efficacy data set meets the Sign test's assumption of being ordinal, matched pairs, and not normally distributed or symmetric. The Sign test showed (Table 17) that the intervention activities did not elicit a significant statistical ($p < 0.05$) change for any Torsion self-efficacy differences. Although there was a difference in the self-efficacy averages pre- and post- module, the statistical analysis reveals that the module did not impact the students virtually as it did in the in-person deployment, Spring 2020 semester. It should be noted that the sample size was n=7, which affects statistical power in correlation calculations, compared to other module deployment sizes.

Table 17: Fall 2020 Torsion Self-Efficacy statistical analysis results from Sign test

	Task	**Ranks (n)**			**Test Statistics**
		Positive	Negative	Ties	p
1.	Create free body diagram for a bar in torsion	2	1	4	1.000
2.	Identify necessary sections for analysis of a bar in torsion	4	1	2	0.375
3.	Calculate max permissible torque based on the allowable shear stress, τ_{allow}, of a bar in torsion	4	2	1	0.375
4.	Calculate max permissible torque based on allowable angle of twist, ϕ_{allow}, of a bar in torsion	5	1	1	0.219
5.	Visualize behavior of a bar subjected to one torque	3	4	0	0.250
6.	Visualize behavior of a bar subjected to more than one torque	5	0	2	0.063
7.	Develop equations of equilibrium for a statically indeterminate bar in torsion with a distributed load	5	0	2	0.063
8.	Develop equations of compatibility for a statically indeterminate bar in torsion with a distributed load	3	3	1	0.625
9.	Develop equations of torque-displacement for a statically indeterminate bar in torsion with a distributed load	5	0	2	0.063
10.	Calculate reaction forces of a statically indeterminate bar in torsion	5	1	1	0.219
11.	Calculate maximum shear stress, τ_{max}, of a bar in torsion	3	3	1	0.625
12.	Calculate maximum shear strain, γ_{max}, of a bar in torsion	4	1	2	0.375
13.	Calculate angle of twist, ϕ, in sections of a bar in torsion	5	0	2	0.063

5.2.3.2.3. Combined Loading Module

Due to the attendance becoming low in the class, the number of participants decreased tremendously. Unfortunately, only two students responded for the post-surveys given in the module. For Self-Efficacy, the pre- and post-module averages were computed to compare the responses of the students (Table 18). There was a negative change in the averages for the first self-efficacy task. This was possibly because the student may have believed they were able to identify the position of points of interest on a 3D structure, but after going through the activity, they may have realized they didn't know as much as they originally thought.

Table 18: Spring 2020 Self-Efficacy survey responses for the 16 Combined Loading tasks

Task	Student 1 (Pre)	Student 2 (Pre)	Student 1 (Post)	Student 2 (Post)	Average (Pre)	Average (Post)
Identify position of points of interest on a 3D structure subjected to load(s)	4	2	3	4	3.0	2.5
Determining contributions of load(s) along multiple sections of a structure	3	4	3	4	3.5	3.5
Visualize behavior of structure subjected to load that results in one or more type of load	3	4	3	5	3.5	3.5
Visualize position of points of interest on structure	3	4	3	5	3.5	3.5
Visualize contribution of load(s) on points of interest	3	4	3	5	3.5	3.5
Illustrating the load contributions on 3D diagram	3	4	3	5	3.5	3.5
Illustrate load contributions on cross section diagram of points of interest	3	4	3	5	3.5	3.5
Develop equations for uniaxial loading due to load on structure	2	4	3	3	3.0	3.5
Develop equations for bending moment equations due to load on structure	2	4	3	3	3.0	3.5
Develop equations for torsion due to load on structure	2	4	3	3	3.0	3.5
Develop equations for shear equations due to load on structure	2	4	3	3	3.0	3.5
Develop equations for stress resultants for each point of interest due to load on structure	2	4	3	3	3.0	3.5
Identifying correct subscript index for stress resultant(s) for points of interest	3	4	3	3	3.5	3.5
Calculate maximum tensile and compressive stresses, at points of interest	0	3	3	4	1.5	3.0
Calculate maximum shear stress, τ_{max}, at points of interest	0	2	3	4	1.0	2.5
Inserting stress components into 3D stress matrix for multiple points	3	0	3	5	1.5	1.5

5.2.3.2.4. Beam Deflection

Similar to the Combined Loading deployment, there was only one student who responded to the post-surveys given. This data will not be displayed due to one sole student participating in the post-surveys.

5.2.3.3. 7.2.3.3 Post-Module Survey Results

5.2.3.3.1. Axial Loading Module

For the Axial Loading module, the about 40% of the students believed they were not comfortable with the subject matter prior to class, and 63% of students responded that the activities contributed to their understanding of the subject matter. About 74% of students thought that Activity 1 contributed to their understanding of Axial Loading, and 63% of students believed Activity 2 contributed to their understanding of Axial Loading. Lastly, 68% of students believed their knowledge of Axial Loading improved upon completion of the activities. Figure 49 shows the distribution of the students' answers for the post-module survey.

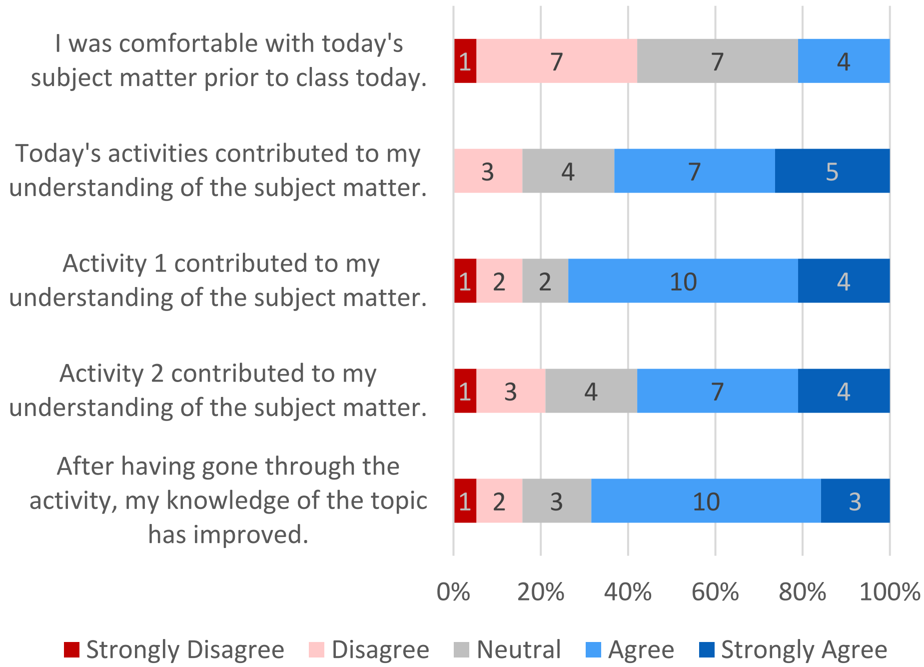


Figure 49: Fall 2020 Axial Loading module Post-Module survey responses by frequency

5.2.3.3.2. Torsion

Due to the reduction of activities due to timing and technical difficulties, there were only three Post-Module survey statements. Figure 50 shows the distribution of the students' responses. The students neither agreed nor disagreed that they were comfortable with Torsion prior to class, and 6 of 7 students agreed or strongly agreed that the activities contributed to their subject matter understanding.

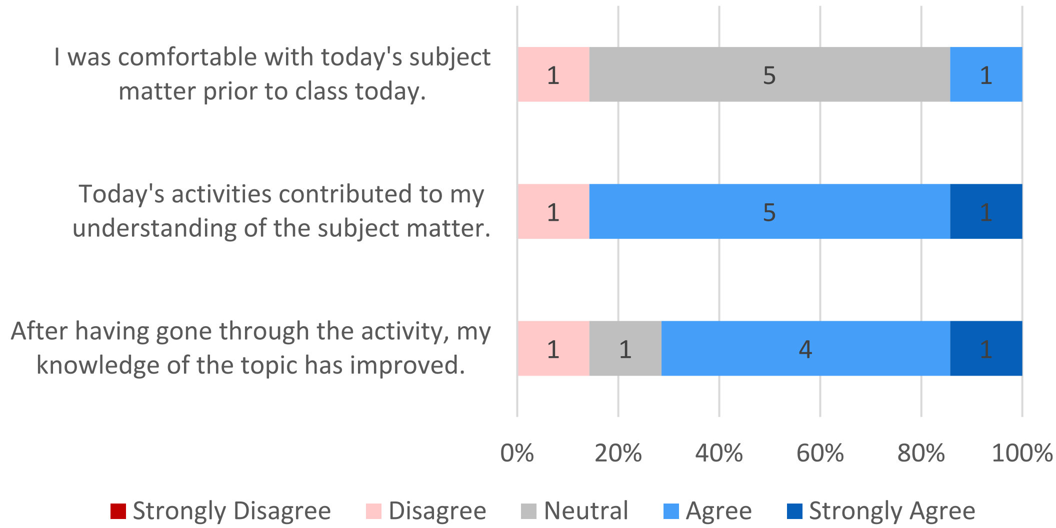


Figure 50: Fall 2020 Torsion module Post-Module survey responses by frequency

5.2.3.3.3. Combined Loading

Although there were fewer students in the Combined Loading module, the students did not feel comfortable with Combined Loading prior to the class. The students agreed the activities contributed to their understanding of the subject matter and one believed their knowledge of Combined Loading increased after going through the intervention activity. Table 19 below shows each students' responses to the three Post-Module statements.

Table 19: Fall 2020 Combined Loading Post-Module student responses

Statement	Student 1	Student 2
I was comfortable with today's subject matter prior to class today.	Disagree	Strongly Disagree
Today's activities contributed to my understanding of the subject matter.	Agree	Strongly Agree
After having gone through the activity, my knowledge of the topic has improved.	Neither agree or disagree	Strongly Agree

5.2.3.4. Module Perception Survey Results

The students who participated in the module perception survey helped the researchers understand the value of the virtual deployment and its components. The Axial Loading module, Torsion module, and Combines Loading module student response frequencies for the Module Perception survey are broken down in the following sections.

5.2.3.4.1. Axial Loading Module

Regarding the virtual learning aspects of the module perception survey (Figure 51: Fall 2020 Axial Loading Module Perception survey responses by frequency), 45% of the students saw the value of viewing the 3D representation via video, and 53% said the video of the 3D model was representative of the types of manipulation they would do. 59% of students said they felt they could understand the scenarios of manipulation of the 3D model as it relates to the problem. These results show that the video showing the multiple perspectives of the manipulation of the model may be a useful alternative to hands-on, in-person 3D model manipulation, if necessary.

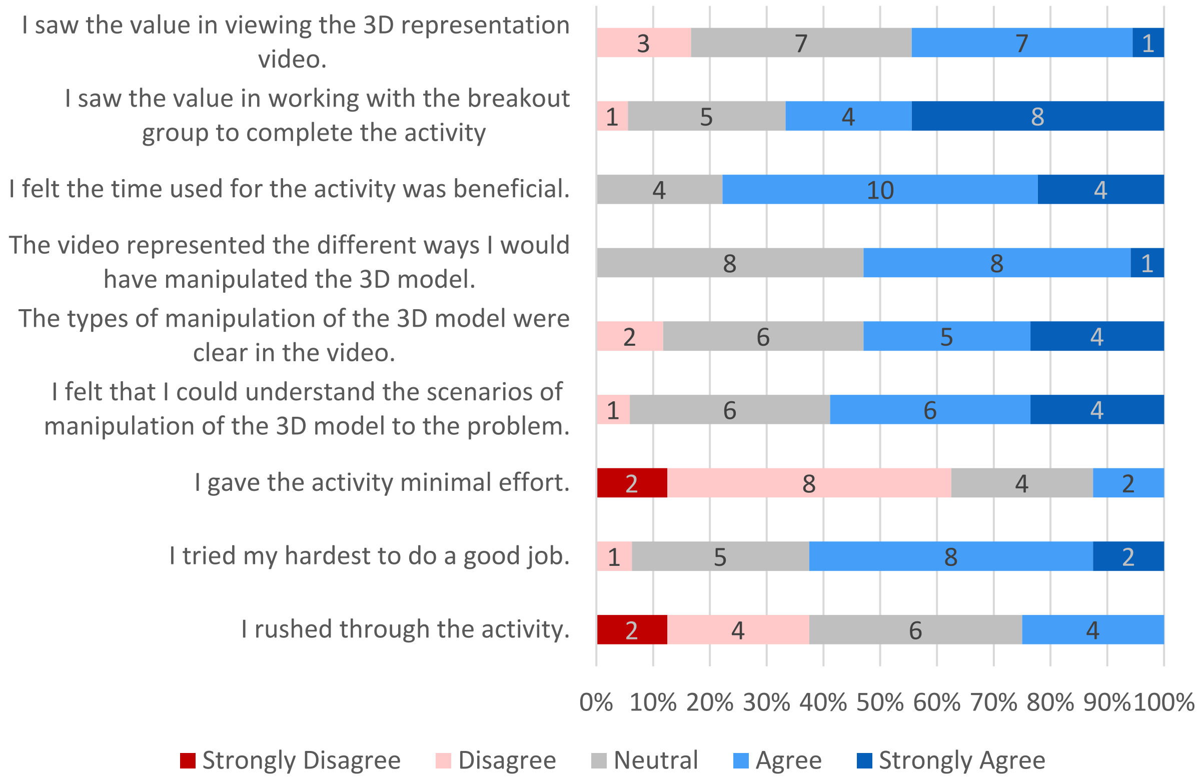


Figure 51: Fall 2020 Axial Loading Module Perception survey responses by frequency

Although the instruction was virtual, the breakout rooms were a huge factor in the activity structure because it allowed for group learning, plus the students getting feedback from the instructors by them visiting the breakout room. As shown in Figure 52 below, over 50% of students agreed to the statements pertaining to the instructors' role in the intervention deployment.

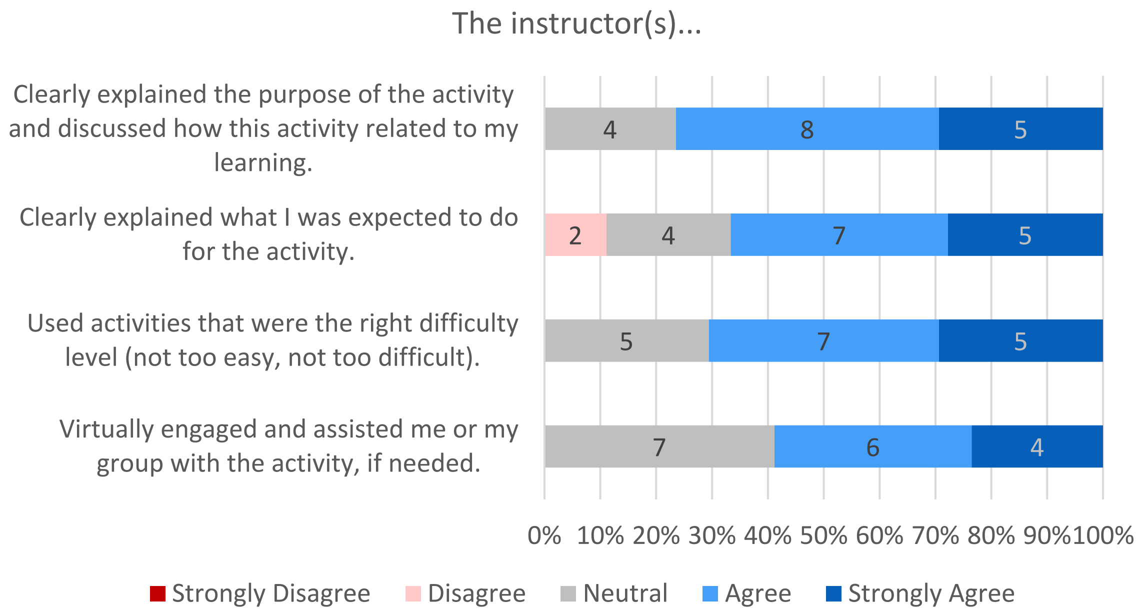


Figure 52: Fall 2020 Axial Loading Module Perception survey responses by frequency pertaining to the instructor(s) role in the module

5.2.3.4.2. Torsion Module

Unlike the Axial Loading module, 81% of the students who participated in the Torsion module saw the value in the 3D representation video. 100% of the participants also agreed the types of manipulation of the 3D model were clear, and they understood the scenarios of the 3D model manipulation as it related to the activity problem. This reveals that for Torsion, implementing 3D video models were helpful to the students in completing their activities. Figure 53 shows the breakdown of the responses of the students.

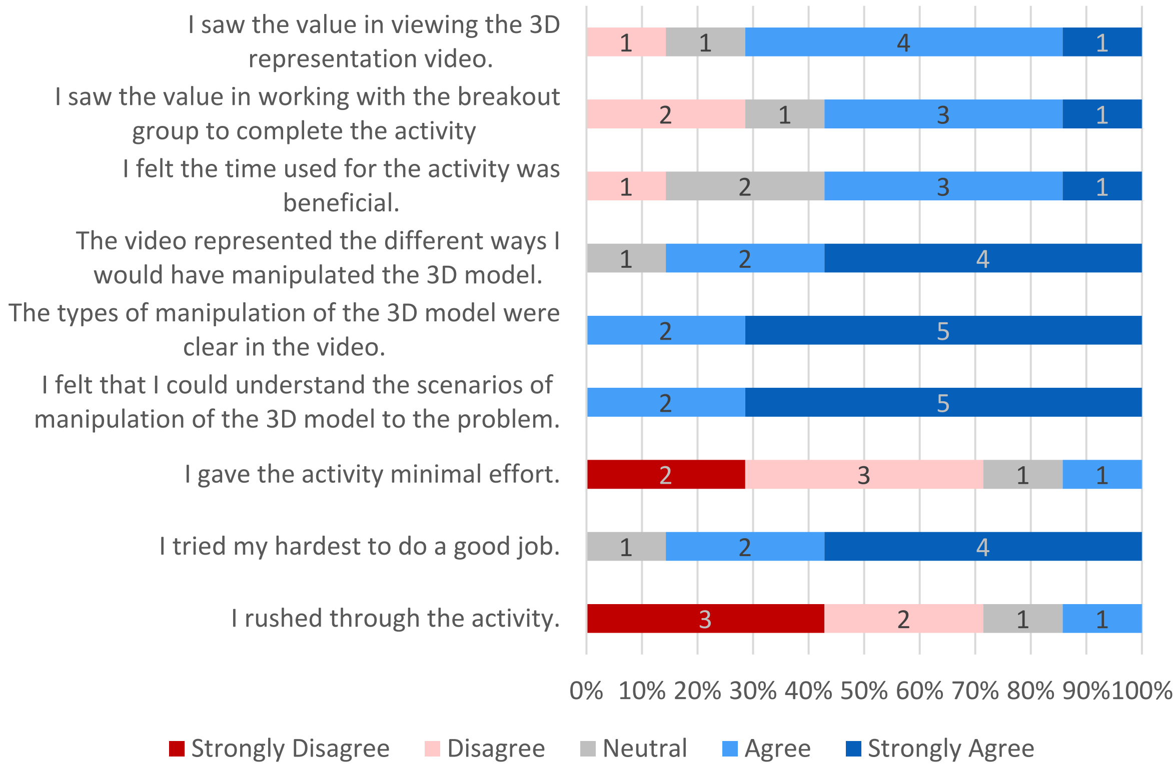


Figure 53: Fall 2020 Torsion Module Perception survey responses by frequency

As shown in Figure 54 below, over 90% of students agreed to the statements pertaining the instructors' role in the intervention deployment. This shows that the students believed the activities were of the right difficulty level, the instructors explained what was expected, and they virtually engaged and assisted the groups.

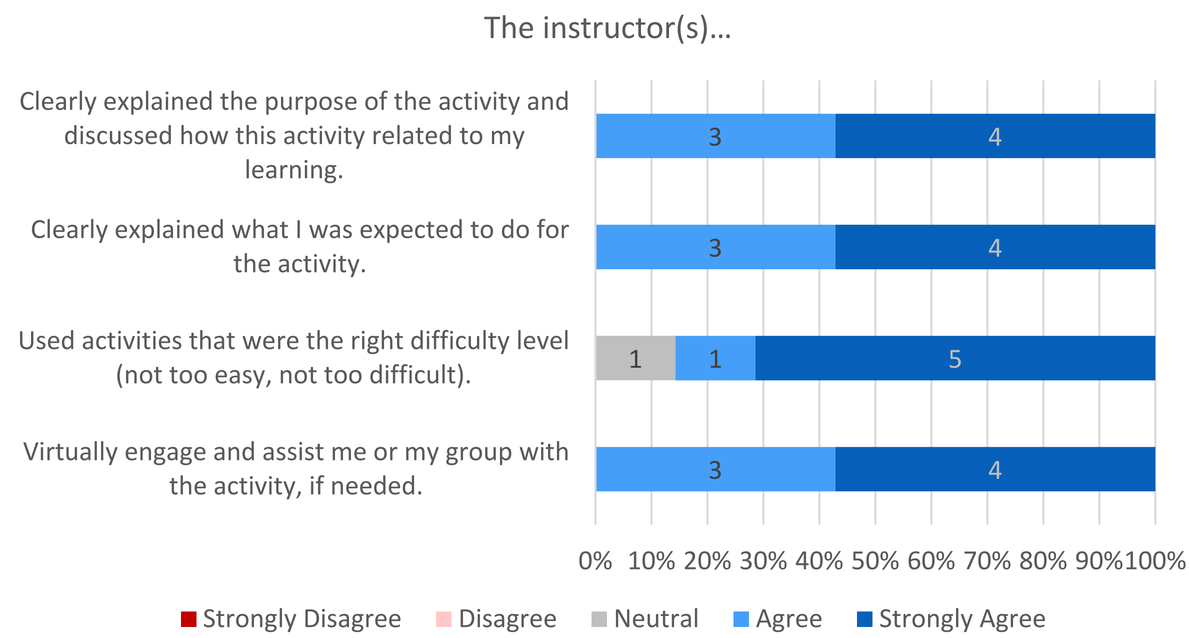


Figure 54: Fall 2020 Torsion Module Perception survey responses by frequency pertaining to the instructor(s) role in the module

5.2.3.4.3. Combined Loading

As noted earlier, there were two student responses for the Module Perception survey. Shown in Table 20 students agreed they saw the value in viewing the 3D representation video and working with breakout groups to complete the activity. The participants felt that they could understand the scenarios of manipulation of the 3D model to the problem. One student believed that the instructor(s) did not explain what was expected to be done for the activity. These results show that although there was ambiguity in the purpose of the Combined Loading module activity, the students saw value in the portions of the module that were adapted for the virtual learning styles.

Table 20: Fall 2020 Combined Loading Module Perception survey responses

Statement	Student 1	Student 2
I saw the value in viewing the 3D representation video.	Agree	Strongly agree
I saw the value in working with the breakout group to complete the activity	Agree	Agree
I felt the time used for the activity was beneficial.	Neither agree nor disagree	Strongly agree
The video represented the different ways I would have manipulated the 3D model.	Agree	Agree
The types of manipulation of the 3D model were clear in the video.	Strongly agree	Strongly agree
I felt that I could understand the scenarios of manipulation of the 3D model to the problem.	Strongly agree	Strongly agree
I gave the activity minimal effort.	Disagree	Strongly disagree
I tried my hardest to do a good job.	Agree	Agree
I rushed through the activity.	Neither agree nor disagree	Strongly disagree
The instructor(s) clearly explained the purpose of the activity and discussed how this activity related to my learning.	Disagree	Strongly agree
The instructor(s) clearly explained what I was expected to do for the activity.	Disagree	Strongly agree
The instructor(s) used activities that were the right difficulty level (not too easy, not too difficult).	Neither agree nor disagree	Strongly agree
The instructor(s) virtually engaged and assisted me or my group with the activity, if needed.	Strongly agree	Strongly agree

5.2.3.4.4. Beam Deflection

This data will not be displayed due to one sole student participating in the post-surveys.

5.3. Summary

This section of the dissertation examined the impact the module had on the students in the Fall 2019, Spring 2020, and Fall 2020 semester deployments. Throughout these semesters, four intervention structures were deployed, and the data was analyzed to understand the effect each of these Intervention Structures.

5.3.1. Fall 2019

In Fall 2019, the deployment of the Intervention 1 structure spanned three crucial topics of mechanics of materials: Stress and Strain, Axial Loading, and Torsion. These consisted of Knowledge Assessments and Post-Module surveys. For these three modules the Knowledge Assessment showed promise of the intervention activities making an impact on the students' knowledge in the respective topics. Although the significance of the difference in means is present, the Knowledge Assessment was replaced with Self-Efficacy to obtain a better understanding of the impact on students' knowledge from their perspective. Although Beam Deflection was not analyzed due to the post-Knowledge Assessment not being completed, the students, from the qualitative feedback, expressed their satisfaction with the shift to the Intervention 2 structure and the advanced material included. From the Post-Module survey results, there was an increase in the students' response in the activities contributing to their understanding of the subject matter. For the Stress and Strain module, there was less than 40% of students who agreed the activities contributed to their subject matter and by the time the Beam Deflection module was deployed, there was about a 65% agreement rate. The students, also, believed Activity 2 was more beneficial than Activity 1 for the Axial Loading and Torsion modules in the Intervention 1 structure. Comparatively, for the Beam Deflection module in the Intervention 2 structure, the students believed both Activity 1 and Activity 2 were equally beneficial to their understanding of the subject matter.

In relation to the control semester, Fall 2018, there was no statistical difference between the Homework and Exam scores for the Fall 2019 Stress and Strain, Axial Loading, and Torsion exams and homework assignment. For Beam Deflection, there was a significant difference between the Fall 2018 and Fall 2019 homework scores. This result shows the potential for the Intervention 2 structure for the module to contribute to the students' knowledgebase.

5.3.2. Spring 2020

For Spring 2020, the deployment consisted of two Intervention 3 structure modules: Axial Loading and Torsion. These modules included self-reported self-efficacy ratings. For both Axial Loading and Torsion, there was a significant difference between the Self-Efficacy scores. This significance shows the students believed the interventions enhanced their knowledge of each topic. The Self-Efficacy scores were correlated with other post surveys. These correlations revealed that the students' change in self-efficacy correlated positively with the belief that the module activities contributed to their understanding of the subject matter. Outside of correlations, the students saw value in working with the 3D model and apparatus for both the Axial Loading and the Torsion module. This large acceptance of the 3D model and apparatus emphasizes the importance of incorporating physical representations of the complex mechanics of materials topics, even if only 50% of students saw the value. The Spring 2020 module Intervention 3 structure was successful as an independent semester deployment.

In relation to the control semester, Fall 2018, the Spring 2020 class deliverable scores were significantly higher for the Axial Loading Exam and Homework scores and Torsion Homework score. This comparison stresses the impact of the modules in the mechanics of materials course because the intervention-exposed semester resulted in higher overall class scores.

5.3.3. Fall 2020

Although the Intervention 4 structure was drastically different from the Fall 2019 and Spring 2020 semesters, there were some significant findings in the data. For self-efficacy, the students felt an impact from the Axial Loading module and not Torsion. There was no statistical significance between the pre- and post-Self-Efficacy responses for Torsion. Although this was the Torsion result for self-efficacy, the students saw more value in the Torsion manipulation videos than the Axial Loading ones. One main result from this semester was the value the students saw in the 3D models and videos they were supplied for the activities. These results revealed that the virtual nature of the activities had a slight impact on the students, and they were able to experience portions of the developed active learning activities, even though they were not in-person.

5.3.4. Overall Semester Module Comparison

Although some of the students were exposed to other topics in the course, the Axial Loading module and the Torsion module spanned all three semesters, and the results show promise that these hands-on, active learning activities can be implemented in the classroom to help students comprehend the topic better. It can be concluded that the intervention iterations had profound impacts on the students' self-reported metrics. Overall, the Spring 2020 deployment of Axial Loading and Torsion in the Intervention 3 structure was the most beneficial to the learning of the subject matter. The correlations made between semesters showed that the metrics of Spring 2020 were consistently higher than the Fall 2019 and Fall 2020 semesters in the Post-Module survey, and class deliverables. The in-person and well-defined objectives of the module resulted in the students being more receptive and developing a deeper comprehension of the subject matter. This data shows that iterative development to improve classroom activities based on student feedback and researcher observations can improve the students' overall knowledgebase of either Axial Loading or Torsion in the topic of mechanics of materials.

CHAPTER 6. DEVELOPMENT AND IMPACT OF GEOMETRIC DIMENSIONING AND TOLERANCING MODULES

6.1. Introduction

Geometric Dimensioning and Tolerancing (GD&T) is a subject in mechanical engineering that is widely used in design for manufacturing. This topic is often taught in a highly theoretical manner, with symbols, abbreviations, and references, and there is a high demand for competency in GD&T for graduates entering the workforce. Students in the first two years of introductory engineering classes are exposed to this topic, and it is a major component of activities that will be taught in the other classes as the students' progress through their education, and beyond in their future engineering careers.

In ME 2110 – Creative Decisions and Design at Georgia Institute of Technology, GD&T is taught as a basis for engineering drawings that students may use in their future classes and in their careers. In this paper, the development process and validation of an intervention for GD&T is presented, designed to help the students obtain a deeper understanding outside of a traditional lecture. The active learning GD&T intervention ties major concepts with hands-on practice for topics that are prevalent in GD&T. Although in industry, coordinate measuring machines (CMMs) are most typically used for inspecting machined parts for the outlined specifications, the students were asked to perform manual methods of inspection during the intervention. By exercising their knowledge of GD&T using manual inspection methods, students were exposed to the necessary background to understand what measurements are needed for part feature inspections and how to translate them to the CMM. The active learning intervention allowed the students to grasp the reasoning behind automated CMM inspection methods. The intervention provided students with a foundational understanding of GD&T, which will allow them to understand the concepts to create part drawings that communicate the correct tolerances needed for manufacturing and assembly.

In this chapter, the effect of careful development and deployment of an active learning intervention focused on GD&T into an undergraduate level class is explored. The intervention included machined parts developed with purposeful characteristics, manual inspection tools to determine if the part meets the specifications, and a step-by-step guided inspection activity. Formative and self-assessments were used to gather participant feedback and performance information to evaluate the educational impact of the developed interventions. The data was analyzed and translated into recommendations for information and concepts to be implemented in future designs of the intervention.

6.2. Activity Development and Components

There are many different factors that prompt those in industry and other manufacturing spaces to invest into in-depth GD&T training, including improved communication, reduction in manufacturing costs and simplified inspections [94]. In manufacturing, inspection of a part's elements relies heavily on the characteristics identified in the parts' drawing. An active learning intervention style lecture was paired with five manual inspections on a machined part to enhance the students' understanding of GD&T concepts within the given time constraints of their course. The objectives and expectations of the students in this intervention were:

By the end of this GD&T Intervention, students should be able to:

- Produce a part drawing that communicates GD&T information to a machinist and inspector
- Demonstrate manual inspection methods for various GD&T characteristics
- Identify and interpret GD&T symbols
- Explain the function of and how to use a Coordinate Measuring Machine (CMM)

The GD&T intervention consisted of three parts (Figure 55): Lecture, Part 1: Part Drawing, and Part 2: Inspection Activity. These sections were accompanied by Pre-Assessments and Post-Assessments that helped the research team to understand if the intervention made an immediate impact on the capabilities of the students. In Part 1, the students were asked to fill in a part drawing based on the information given about the manufacturability and function of the part. In Part 2, the students performed a hands-on manual inspection activity based on given part drawing specifications and methods outlined. These assessments are described in detail later in the chapter.

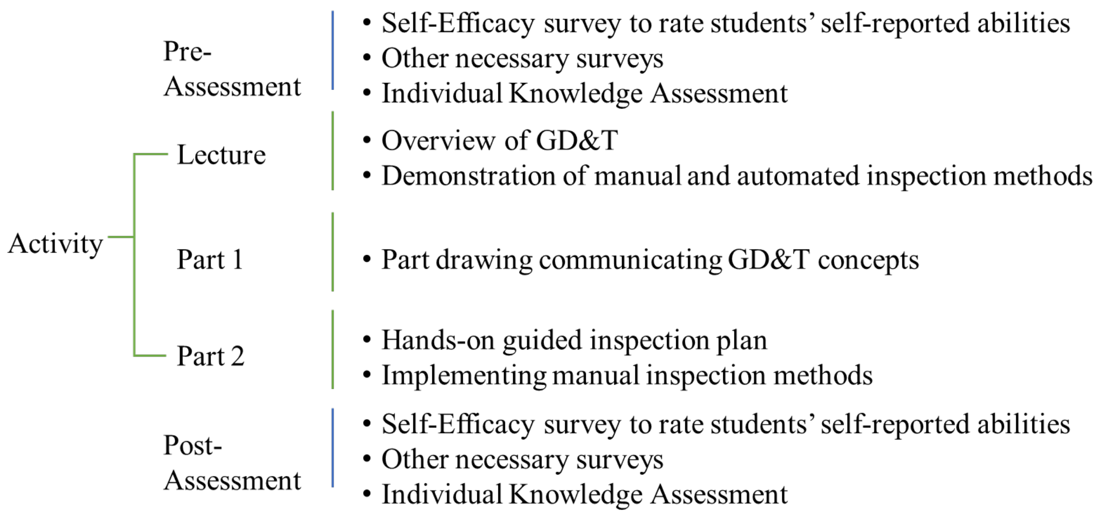


Figure 55: Breakdown of GD&T Intervention components

6.2.1. Lecture

The lecture about GD&T basics was a crucial part of this study and was delivered by two lecturers. The lecture was used to provide participants with the information needed to perform the part drawing and hands-on activity portions of the intervention. The lecture framed the GD&T information in the context of the history of manufacturing in order to explain why GD&T standards are used in industry. By explaining the evolution of manufacturing from manually created single parts, to the beginning of mass production, to the need for accurate mass-produced parts, the need for GD&T standards became clear. The lecture included the purpose and selection process of datums so that students would be able complete the part drawing when given the physical part. For the same reason, symbols and feature control frames were covered next before the in-depth explanation of the different types of tolerances. These tolerances included: datums, flatness, perpendicularity, parallelism, hole size, position of a hole, and profile of a surface. The types of tolerances selected for in-depth instruction were the ones utilized in the hands-on activity, as outlined in the following section. The detailed instruction contained a description of the tolerance with visual aids, an example of its usage in an engineering drawing, and methods used to measure the tolerance. Measurement methodology included high-end examples, such as a coordinate measuring machine (CMM), less advanced mid-range methods, and the low-cost methods utilized in the hands-on portion of the activity.

6.2.2. Machined Part

In Part 1 and Part 2, students used two mating machined parts (Part A and Part B) as visuals and tools for collaboration and inspection, as shown in FigFigure 2. The machined part was designed to mimic the form and function of a part that would commonly be produced in a machine shop. The parts have interlocking features: Part A has two holes in the center, and Part B has a slot and a hole that line up with Part A's holes to allow dowel pins to be inserted. Hole/slot alignment is a preferred and common way to align two parts without resulting in over constraining and higher machining costs, while still maintaining precision location. Understanding how to use GD&T to effectively communicate datum features and part tolerances for hole/slot alignment is a useful skill for mechanical designers. Part A and B, shown in Figure 56, have common features - the part is a flat rectangular block with four bolt holes in each corner, and one corner cut at a 45-degree angle for orientation. The 45-degree angle notch is to help students to reference part orientation in regard to the engineering drawing. Four holes were added around the hole/slot alignment feature to give the students additional features to learn from. Understanding how to use GD&T to communicate how to manufacture this part to a mechanic is a useful skill for developing engineers to ensure part functionality. Having additional bolt holes around a hole/slot alignment can be common for parts that require redundancy in the event the dowel pins fail.

In this intervention, Part B is the machined part of focus. Part B was the only machined part used for inspection due to time constraints, social distancing restrictions in the classroom, and because the inspection method for Part B incorporated a functional gauge for the hole/slot combination, unlike Part A, thus introducing the students to a larger variety of inspection techniques.

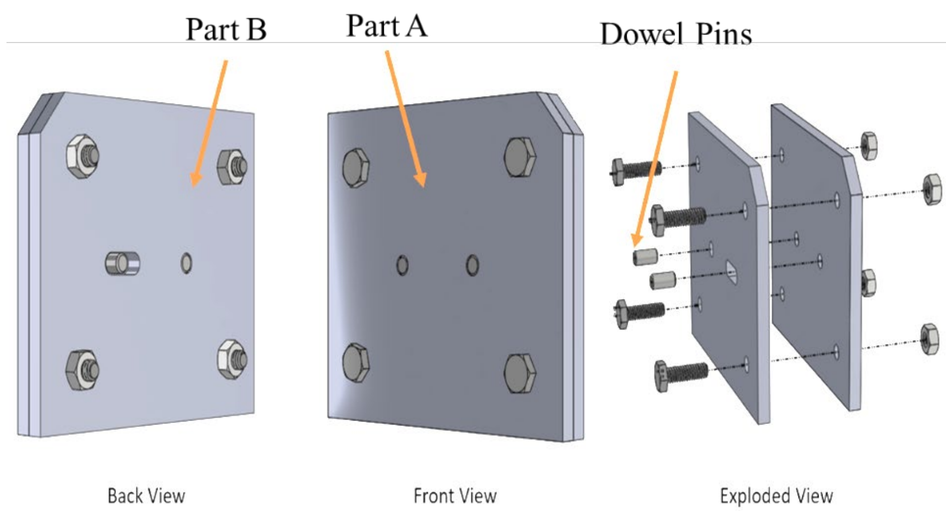


Figure 56. Back, front, and exploded view of Parts A and B

6.2.3. Part 1: Part Drawing

Part 1 was developed with the intention that the participants would apply the characteristics and concepts outlined in the lecture to a physical part drawing of the machined part, as shown in Figure 57. The students were given a blank part drawing to fill in part specifications. The specifications included in the part drawing were intended to be guides for understanding how specifications translate from form and function to certain necessary inspection methods. The activity contained an explanation of how the parts were intended to be used in order to help students understand how the certain part features interfaced with others.

Figure 57. Machined Part B with hole and slot and four corner holes

Participants were given a packet of paper materials for the intervention. The packet supplied a list of GD&T characteristics and terms, such as datums and tolerances, that were expected to be seen in the drawing, once filled in. The students were tasked with filling the blanks in based on the information given in the packet. This task was designed to be completed individually and to the best of their ability. After the students completed the activity, they were given the correct part drawing with the necessary specifications, as shown in Figure 58, to inspect and measure the machined part for Part 2: Inspection Activity.

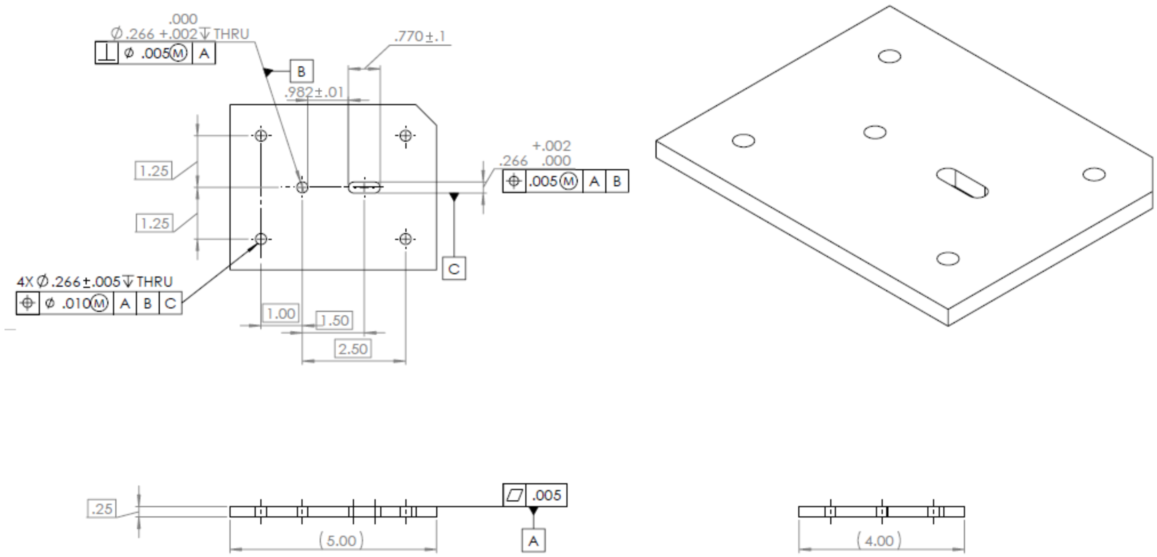


Figure 58. Part drawing of Machined Part B

6.2.4. Part 2: Inspection Activity

The inspection activity was developed for the participants to be able to perform a reasonable manual inspection of the aluminum part (Figure 2 above) given the part drawing. A manual inspection is important because one will be able to gauge if a part meets the specifications (or “is in-spec”), but also will be able to verify the CMM if they suspect something may be wrong or mis-calibrated. Although, inspections in the present day are typically done using the CMM, these manual inspection methods were incorporated into the activity to give the students an understanding of how the different characteristics are tested and how certain features of a part are measured. It is important for the students to be able to interpret GD&T in part drawings regardless of inspection method.

The five inspection methods and materials used for the inspection activity are outlined in Table 21 . These inspection methods were selected and developed due to the low cost (the price of one kit was slightly over $300), as well as the accessibility of the methods. Many of the methods could be performed without specialized equipment and would therefore be more applicable to future situations in which the participants need to verify if a part is manufactured correctly but may not have high-cost specialized measurement equipment available. The combination of these materials for inspection will be comparable to a CMM inspection method of the same features.

Table 21. Description of inspection activities

Feature	Description of Inspection Activities
Flatness	Participants used the granite slab and 1-2-3 gauge blocks to level the feature, then swept the surface with the horizontal dial indicator to determine if the part was flat.
Slot size	Participants used a caliper to measure the major and minor diameters of the stadium-shaped slot to determine if the dimensions were in spec.
Hole size	Participants used the “no-go” gauge pins to check that the hole diameter was within the upper tolerance. They used a “go” gauge pin to check the lower tolerance.
Hole position	Participants measured the distance between holes by placing “go” gauge pins in two holes. The calipers were then used to measure the distance between the pins, while using the machinist’s square to ensure that the caliper was held parallel to the part edges. Participants took measurements in both the x- and y-direction before performing an MMC calculation to ensure that the hole position was within spec.
Position of hole and slot	Participants used the custom steel functional gauge to determine if the position of the hole and slot were within spec. If the gauge was able to be fully inserted into the cutouts, then the part was in spec.

Each participant was given a kit of inspection materials to obtain measurements of their aluminum part and determine whether each measurement was in- or out-of-spec according to the correct part drawing granted after the student completed Part 1 of the activity. The kit consisted of go/no-go gauges, a granite block, a machinist’s square, a horizontal dial indicator, a functional gauge, calipers, and a 1-2-3 gauge block. Each inspection method had written instructions for use of materials to obtain the necessary measurements. Along with the instructions, there is a table where the measurements are recorded. In the beginning of the Part 2 section of the packet, there was a master table with space to put necessary information needed to determine if the part's features were in spec. For brevity, two methods will be discussed in this paper: position of the hole and slot and the flatness inspection method.

For the position of hole and slot method, the students were given a custom, machined steel functional gauge shown in Figure 59. This functional gauge was essential for determining the accuracy of the hole position in relation to the slot position. If the gauge was able to be fully inserted into the hole and slot of the aluminum part, then the part was defined as in-spec, and the students were asked to note this in their activity packet. This inspection method is shown in Figure 60.

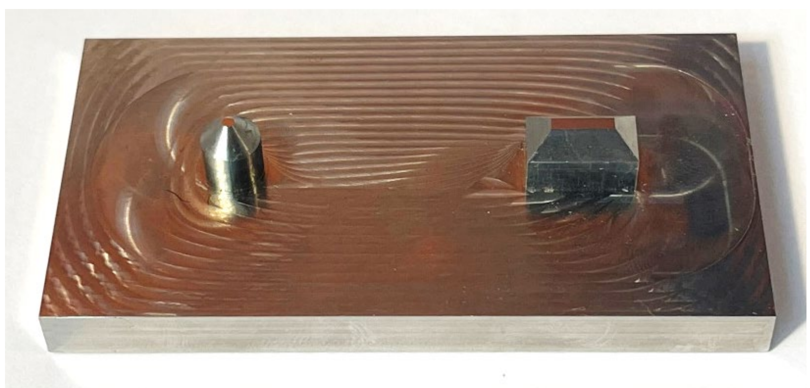


Figure 59. Machined functional gauge used for position of hole and slot inspection method

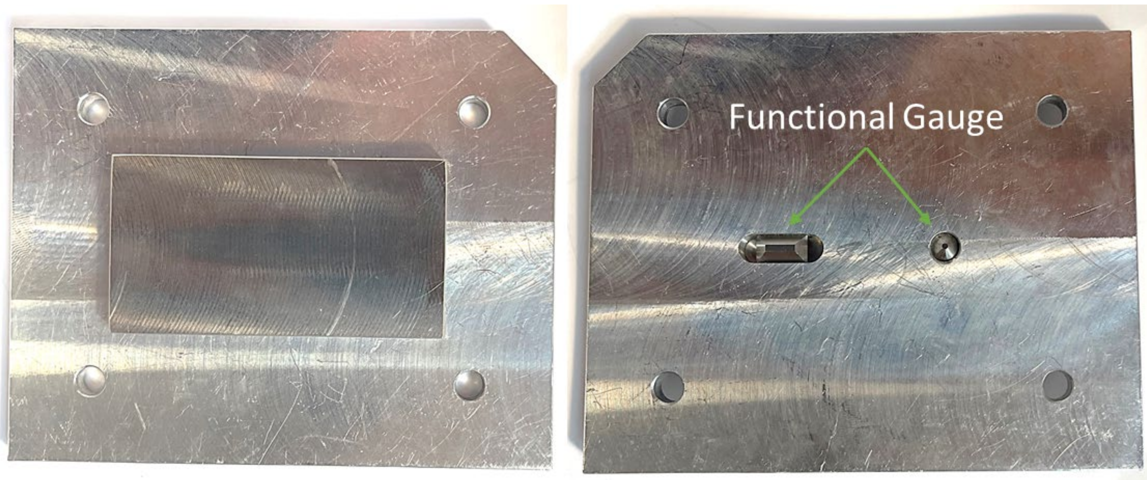


Figure 60. Position of hole and slot inspection method using functional gauge from the front view (left) and back view (right)

For the flatness inspection method, the students used a granite slab, two 1-2-3 gauge blocks, and a horizontal dial indicator, all shown in Figure 61. The granite slab had precise manufacturing specifications; therefore, making it a good surface to use for a leveled plane in comparison to the wooden tables used in labs. The 1-2-3 gauge blocks are used as a second level feature for the machined part rests on top of the gauges, which rests on top of the granite block. These second level features are needed to elevate the machined part to use the horizontal dial indicator. The horizonal dial indicator was swept to four points on the surface of the machined part to determine the part's flatness. The comparison of the change in reading of the four points from the calibration point to the flatness specifications on the part drawings determined if the part was in spec or not. This inspection method is shown in Figure 62.

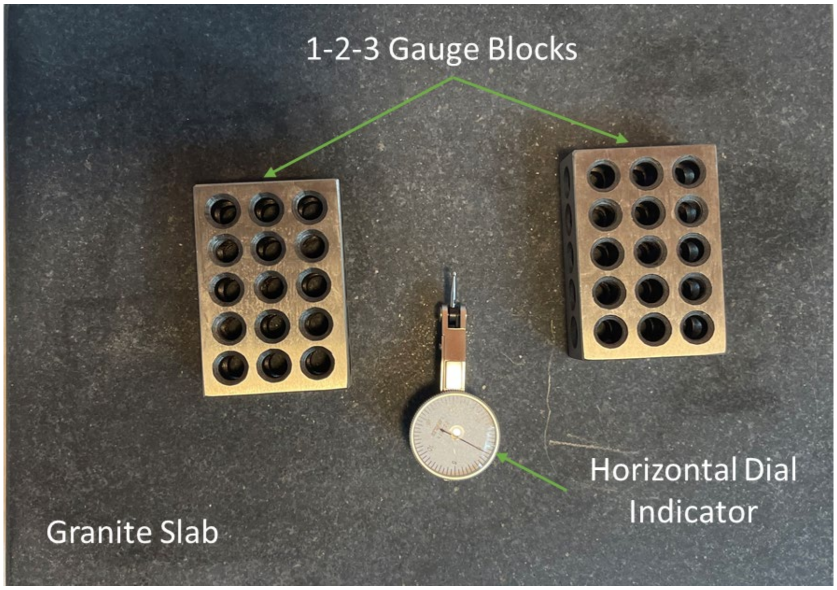


Figure 61. Materials used for flatness inspection method

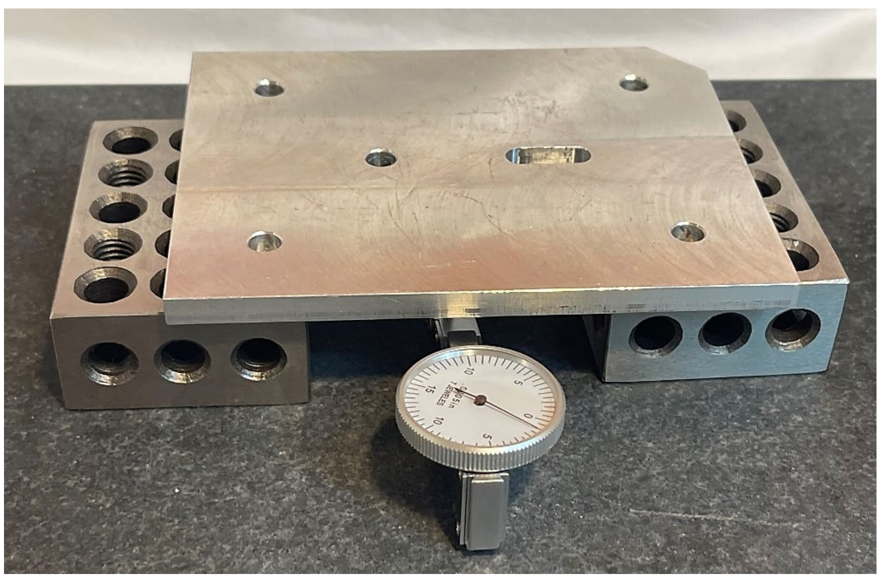


Figure 62. Flatness inspection of Machined Part B

6.3. Assessments and Surveys

Two types of assessments were used to help the researchers understand the impact of the intervention on the students: a Knowledge Assessment and a Self-Efficacy Survey.

Two surveys were used to understand if the students believed the activities contributed to their knowledgebase: Exit Survey and Perceived Value survey.

6.3.1. Knowledge Assessment

The students were given the same Knowledge Assessment before and after the intervention. The Knowledge Assessment questions were tailored to the skills or knowledge students were expected to gain during the lecture and activities given. The assessment consisted of eight questions that asked the students to identify geometric characteristics and symbols, fill in the necessary part drawing characteristics, accept or reject a part, and other topic knowledge students would gain from the activities. The questions were created based on the lecture teachings and topics that were covered. For the part drawing (Figure 9), the students were given instructions on how to fill in the necessary parts of the feature control frame. This was added to help the researchers understand if students understood what the best method is to assign datums and recognized the placement and dimensioning associated with the GD&T characteristic.

4. Fill in the necessary information into the feature control frame (FCF) for the following part
   a. Establish the right-hand face in the left-side view as datum feature A.
   b. Label datum features B and C.
   c. Label the primary and secondary datums missing in the FCF.
   d. Label the GD&T characteristics for profile of surface, position, flatness, and perpendicularity.

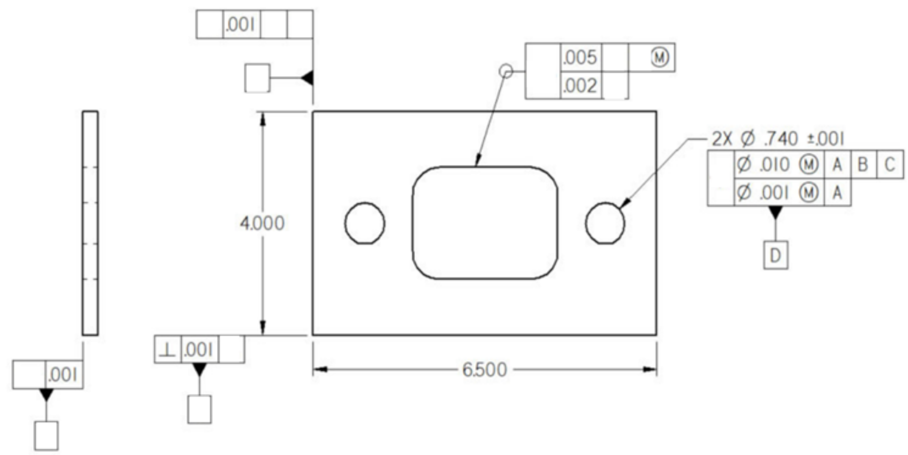


Figure 63. Question 4 (Part Drawing) from the Knowledge Assessment

The students were scored out of 29.5 points. Each blank of the part drawing was worth 0.5 points. The free response questions had 0.5-1 point flexibility if the student answered the question, but did not have a clear, concise answer. The GD&T characteristics and symbols in the other questions were worth 1point each. The Knowledge Assessment and the corresponding points system were created to distribute the weight of the information asked of the students. This helped the researchers understand what concepts the students may not have grasped, as well as avoid penalization of the overall student score if one concept was not grasped over others.

6.3.2. Self-Efficacy

The students were given a self-reported Self-Efficacy survey before and after the Knowledge Assessment to help the researchers understand their confidence in their ability to complete certain tasks. These tasks were specific to the expectations of topics or methods students should have learned in the activities. Self-efficacy was used as an alternative method of gauging the students' progression from before to after the activities. The students rated their confidence of their ability to complete the following tasks on a scale from 1 (Cannot do at all) to 5 (Highly certain can do). The tasks asked were:

1. Identify Geometric Dimensioning & Tolerancing (GD&T) symbols
2. Choose correct reference datum based on part description
3. Calculate Least Material Condition (LMC) of specific hole
4. Calculate Maximum Material Condition (MMC) of specific hole
5. Create a Feature Control Frame (FCF)
6. Interpret a Feature Control Frame (FCF)
7. Measure the flatness of a feature using horizontal dial indicator
8. Measure the perpendicularity of a hole using gauge pin and dial indicator
9. Measure hole position using calipers and machinist square
10. Measure a hole size using go/no-go gauge pins
11. Measure a hole position using a gauge pin calipers and a machinist square
12. Verify the position of features relative to each other using functional gauge
13. Accept or reject features based on measurements conducted
14. Use a manufacturing method to decide the tolerance of a hole
15. Understand how to set up a part in a CMM (Coordinate Measuring Machine)

6.3.3. Exit Survey

The students were given an exit survey at the end of the intervention. The survey asked the students 5 Likert- scale questions and three open response questions. Five of the questions asked the students to agree or disagree (1 – strongly disagree and 5 – strongly agree) to if the activities contributed to the students' knowledge, and the sixth question asked the students to rate the usefulness of the overall intervention. The three open response questions asked what the students believed were the best parts of the intervention and what they believe the researchers could do to make sure the intervention in better in the future.

6.3.4. Perceived Value

The Perceived Value survey asked students about components that were essential to the intervention, and students indicated whether they saw value in those components. The survey is broken into two distinct parts: the role of the student and the role of the instructor. The survey is a 5-point Likert scale (1 – Completely disagree, 2 – Somewhat Disagree, 3 – Neither agree nor disagree, 4 – Somewhat Agree, 5 – Completely Agree).

6.4. Activity Implementation

The activities were implemented in two 3-hour lab sections of the ME2110 course. The activity took roughly two hours of the lab session. Participation was strictly volunteer based, and the students were compensated with extra credit if they participated. The implementation team consisted of two people: a ME2110 Lead Teaching Assistant (TA) and a Graduate Researcher. The Lead TA gave the students a sense of familiarity when it came to instructors so they would not feel intimidated. The Graduate Researcher's role was to observe and help educate the participants of the study, while making sure the study was running smoothly. Both members of the team were involved in teaching the lecture, distribution of activities and equipment, and assisting the students with questions.

The intervention was broken down into five parts (Figure 64): Pre-Knowledge Assessment (which incorporated the pre Self-Efficacy survey), Informational Lecture, Part 1: Part drawing, Part 2: Measuring Activity, and Post-Knowledge Assessment (which incorporated the post Self-Efficacy survey, Exit survey, and Perceived Value survey). The Knowledge Assessments were given at the beginning and end of the sessions. The students were given 10 minutes to complete each of the Knowledge Assessments and accompanying surveys. They were, then, given a 45-minute lecture of an overview of the importance of GD&T, main concepts, and how measurements are done manually and on the CMM. After, the lecture, the students were given 20 minutes to complete Part 1 and 40 minutes to complete Part 2 of the intervention.

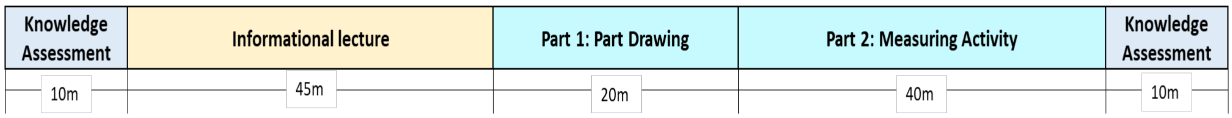


Figure 64. Schedule of Activities

6.4.1. Part 1: Part Drawing

The first part of the intervention was completed individually. During this time, the students were asked to spend about 20 minutes understanding the functionality of the part and filling in the respective GD&T symbols for the part drawings. After the students completed this task, their part drawing was photographed to make sure they did not go back and change anything, and they were given a correct part drawing to use for measuring activities in Part 2.

6.4.2. Part 2: Inspection Activity

For Part 2, the students were divided into groups of 2-3 students. Each student had their own physical machined part to measure, but shared inspection materials and techniques. Group learning was incorporated to encourage students to think about and share ideas that could help them successfully inspect the machined parts. The material that was mainly shared by the group was the granite block. Each student had their own gauges, calipers, and other necessary materials. Half of the machined parts were created in adherence with a master part drawing, while the other half of the parts were created in violation of the drawing in order to test whether the groups of participants were able to differentiate between in-spec and out-of-spec parts.

6.4.3. Observations

The first session happened in the morning while the second session happened in the afternoon, therefore the implementation team was better equipped for running the evening session due to the lessons learned in the first session. In both sessions, the implementation team realized that the time allotted was a crucial factor in the experience of the students in the study. The timing of the activities was not sufficient for the students to work on everything given. Since this was the first time many students were exposed to an in-depth GD&T lecture and activity, the students seemed confused and required more explanation than the provided lecture. This took up much of the time, and the students tried their best to complete as much of the activities as possible.

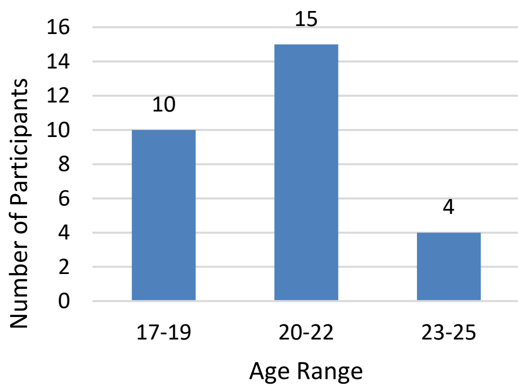
For Part 1, the students did take the time to fill out the part drawing, but because it was not mandatory to move forward, they did not feel the need to struggle on the activity. Although, the students were given a list of features to incorporate in the drawings, many students chose not to fill in the majority of the part drawing and instead move on to the second part. For Part 2, the students were not able to complete all parts in the time allotted. They had many questions about how to set up the inspection tools for the various inspection parts. The main inspection method requiring instructor help was the flatness inspection. This involved a horizontal dial indicator and the students setting the inspection tools up in a specific manner to inspect the part. This prompted the instruction team to help walk the students through the instrumentation set up and to display the relevant slides from the lecture on the screen so that students were able to reference them. Instead of reading the instructions in the packet, many students asked the instructors to explain the procedure to them or attempted to figure it out on their own by experimenting with the provided materials. Many of the students were not able to get to the inspection of hole size activity due to time constraints.

6.5. Results

The results of the GD&T intervention activity are extensive. The results presented in this paper will explore the demographic composition of the classes, the surveys the students completed, the activities the students participated in, and the correlations between these different data channels. The results are presented next.

6.5.1. Demographics

In this study, there were 29 participants in total, but one chose not to disclose demographic data. The first session had 11 participants, and the second session had 18 participants. Overall, there were 22 men and 6 women participants. The primary age range identified by the participants was 20-22 years old. The participants' year in their undergraduate had an average of 2.75 years and ranged from 2-5 years. The students were all mechanical engineering majors besides one student from the college of business who is pursuing a minor in mechanical engineering. There were 14 students with one or more minors spanning at least six different colleges at Georgia Tech.



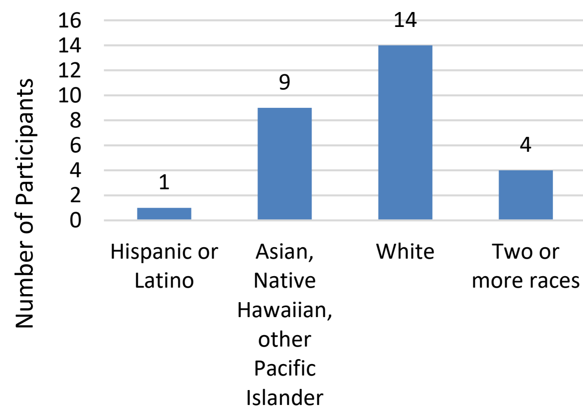
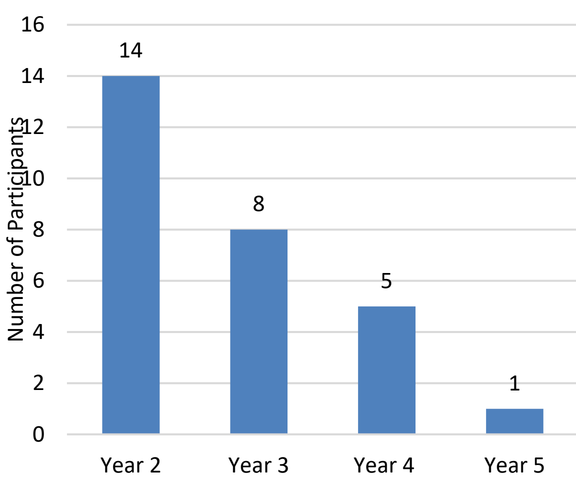


Figure 65. Age Range of Participants (left) and the Race and Ethnicity distribution of participants (right)



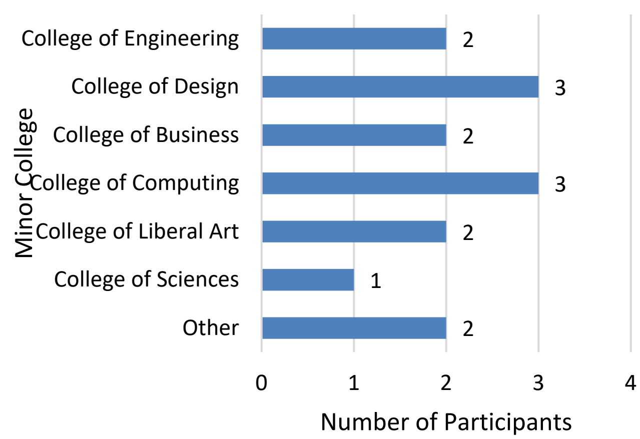


Figure 66. Year of undergrad distribution of participants (left) and minor college enrollment distribution of participants (right)

For GD&T experience, 16 participants had prior experience with GD&T. Most of the prior GD&T experience was from class, most notably the ME1770 class at Georgia Tech. Figure 67 shows the breakdown of the types of GD&T experience the participants had previously. Every participant had hardware tool experience, ranging from the band saw and drill to a

CNC machine. Every participant had experience with a CAD or design software, ranging from SolidWorks and Inventor to Adobe Suite.

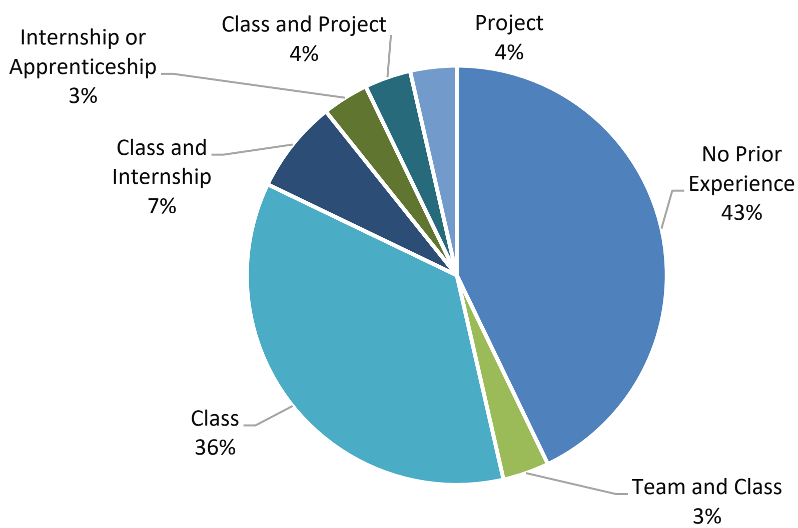


Figure 67. Prior GD&T experience breakdown for participants

The participants were asked their how many years of fabrication-related and design-related experience they had, excluding the ME2110 class deliverables. Most participants did not have either fabrication or design-related experiences outside of class. Figure 68 shows the years of experience distribution for both design and fabrication. Only one participant had more than two years of both fabrication and design experience. The other participants had a combination of outside projects, internship experience, team experience, and research. Figure 69 and Figure 70 breaks down the experience of those who reported theirs.

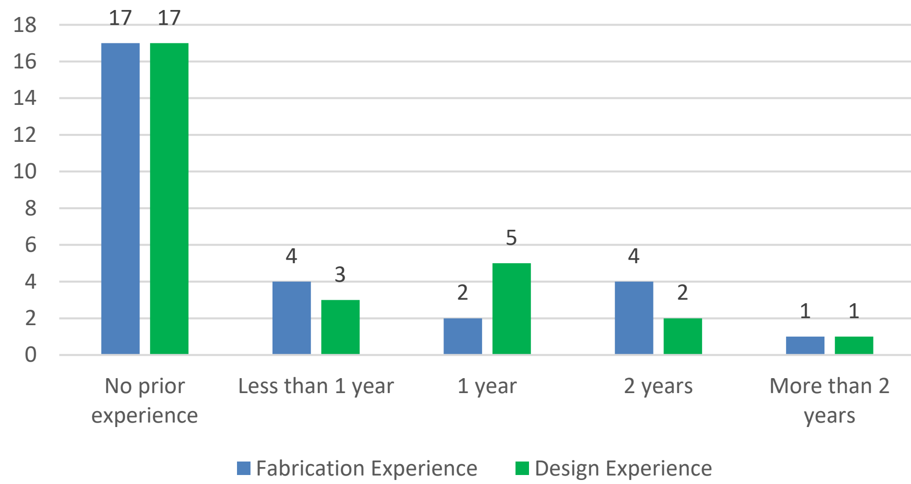


Figure 68. Years of fabrication and design-related experience of the participants

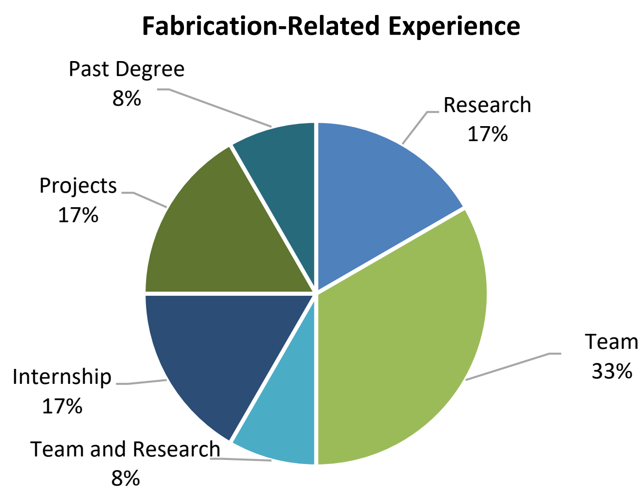


Figure 69: Breakdown of fabrication-related experience of the participants

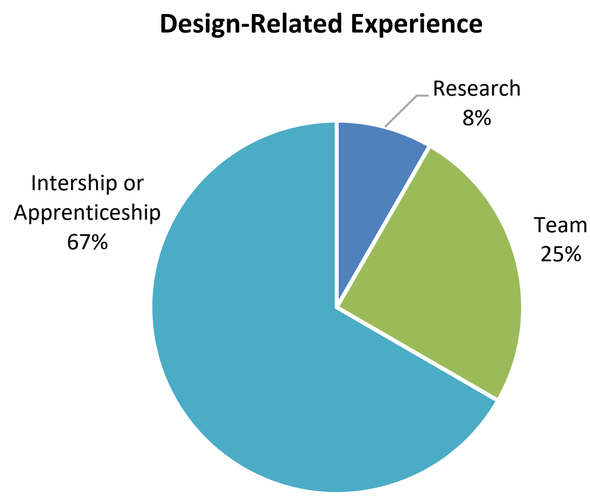


Figure 70. Breakdown of design-related experience of the participants

6.5.2. Self-Efficacy

Self-efficacy was measured with surveys before and after the students were introduced to the intervention. The survey asked the students to rate their degree of confidence to do the tasks associated with GD&T using a Likert scale response from 1-5 (1- Cannot do at all, 3- Moderately can do, and 5 – Highly certain can do). The averages of the scores were computed for each self-efficacy task before and after the intervention activities were given. Figure 71 shows the comparison of averages for all 15 tasks. All tasks had at least a 1-point change in average except task 9, which had a 0.4-point change and task 11, which had a 0.6-point change.

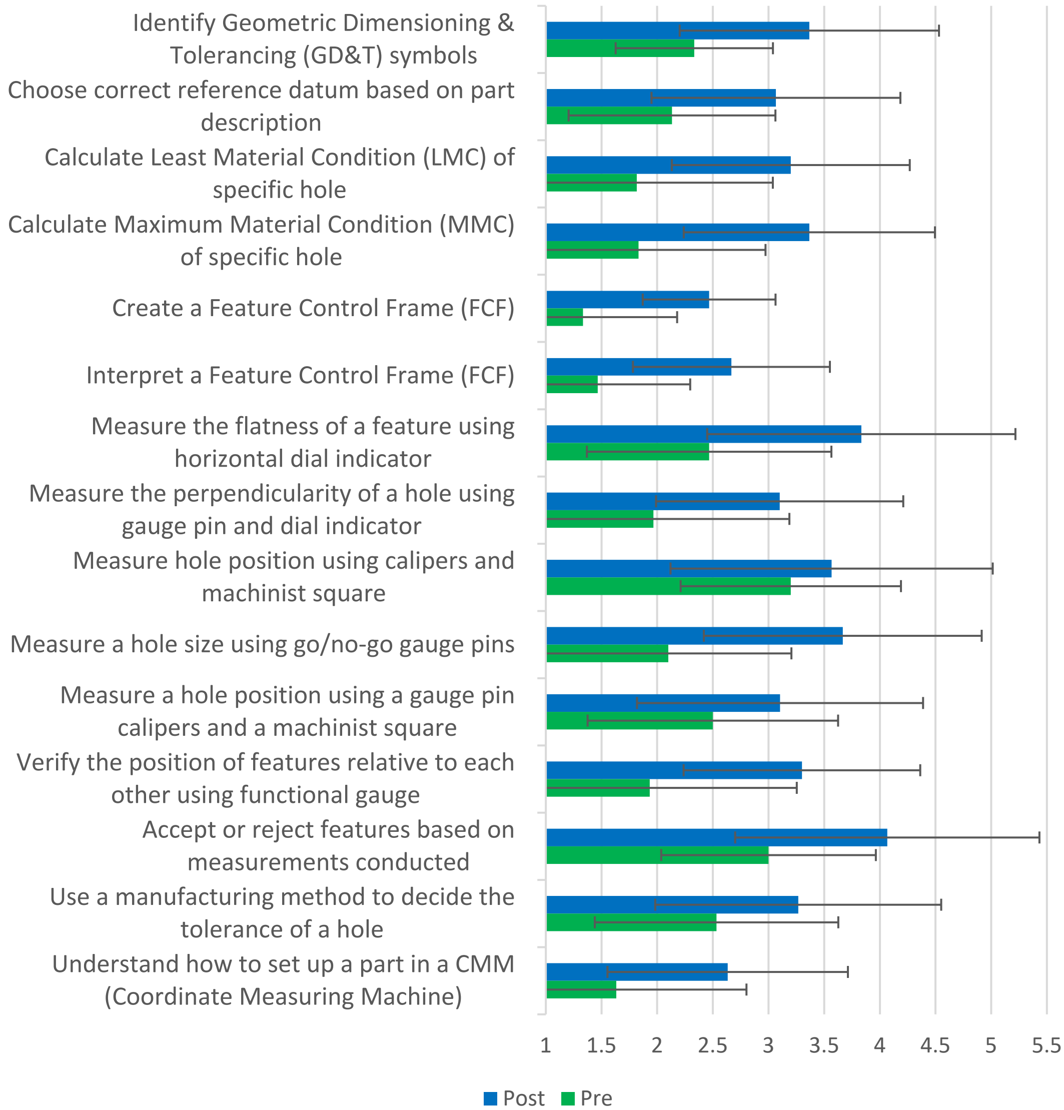


Figure 71. Average pre- and post- self-efficacy rating with standard deviation based on students' self-reported confidence; Error bars show ± one standard deviation

A Sign test was chosen to analyze pre- and post- Self-Efficacy responses due to the ordinal nature of the Self-Efficacy survey, the pre- and post-scores are matched pairs, each data set is of a non-normal distribution, but the symmetry of the differences aren't the same. The test was used to understand the significance of the total groups' change in average Self- Efficacy (Table 22). The hypothesis is there is a difference between the pre-intervention and post-intervention self-efficacy scores of the students for the GD&T activities. The Sign test showed that the intervention activities did elicit a significant statistical ($p < 0.05$) change for all Self-Efficacy tasks, except task 9 ($p = 0.481$). For task 9, due to time, most students were not able to complete the inspection of the hole position(s).

Table 22. Results of Sign test with negative and positive ranks breakdown for the 15 Self-Efficacy tasks.

	Task	**Ranks (n)**			**Test statistics**	
		Positive	Negative	Ties	Z	*p*
1.	Identify Geometric Dimensioning & Tolerancing (GD&T) symbols	24	3	2	-3.849	0.000**
2.	Choose correct reference datum based on part description	22	2	5		0.000**
3.	Calculate Least Material Condition (LMC) of specific hole	23	0	6		0.000**
4.	Calculate Maximum Material Condition (MMC) of specific hole	25	0	4		0.000**
5.	Create a Feature Control Frame (FCF)	22	2	5		0.000**
6.	Interpret a Feature Control Frame (FCF)	20	3	6		0.000**
7.	Measure the flatness of a feature using horizontal dial indicator	21	1	7		0.000**
8.	Measure the perpendicularity of a hole using gauge pin and dial indicator	20	2	7		0.000**
9.	Measure hole position using calipers and machinist square	11	7	11		0.481
10.	Measure a hole size using go/no-go gauge pins	21	2	6		0.000**
11.	Measure a hole position using a gauge pin calipers and a machinist square	12	3	14		0.035*
12.	Verify the position of features relative to each other using functional gauge	20	2	7		0.000**
13.	Accept or reject features based on measurements conducted	18	4	7		0.004*
14.	Use a manufacturing method to decide the tolerance of a hole	17	3	9		0.003*
15.	Understand how to set up a part in a CMM	19	2	8		0.001**

*significant (p<0.05); ** highly significant (p<0.001); blanks in *Z* column indicates binomial distribution was used

6.5.3. Knowledge Assessment Results

The Pre-Intervention Knowledge Assessment and Post-Intervention Knowledge Assessment were done before and after the intervention. These assessments were the same.

The total possible score for the assessments was 29.5 points. The overall average Pre-Intervention Knowledge Assessment score was 25.6 ± 13.7% correct answers, and the overall average Post-Intervention Knowledge Assessment score was 56.2 ± 16.3% correct answers.

Due to the data being continuous and matched pairs with no significant outliers, paired t-tests were conducted to compare the Pre- and Post-Intervention Knowledge Assessment scores. The hypothesis is there is a difference between the pre-intervention and post-intervention Knowledge Assessment scores of the students for the GD&T activities. The paired t-tests were run by total points possible for the overall score, as well as each assessment question. Table 3 shows the breakdown of the paired t-test results with the average scores and standard deviation of each. Due to the means of the overall Pre- and Post-Intervention Knowledge Assessment scores, and the direction of the t-value ($t(28) = -12.321$, $p < 0.001$), it can be concluded that there was a statistically significant improvement of the Post-Intervention Knowledge Assessment following the activities. There is a statistical significance ($p < 0.05$) in the means comparison of each individual question besides Question 3 ($t(28) = -0.972$, $p = 0.339$), which focused on Material Modifiers, and Question 6 ($t(28) = -1.609$, $p = 0.119$), which focused on the difference between parallelism and flatness.

Table 23. Paired Samples t-tests comparing Pre-Assessment and Post-Assessment Scores

Paired Question (Total Points)	Pre-Assessment Mean	Pre-Assessment Standard Deviation	Post Assessment Mean	Post Assessment Standard Deviation	df	t	p
Overall Score (29.5pts)	7.42	4.30	16.18	5.69	28	-12.321	0.000**
Question 1 (8pts)	2.41	2.18	5.45	1.55	28	-6.318	0.000**
Question 2 (7pts)	2.31	0.97	4.62	1.45	28	-8.068	0.000**
Question 3 (2pts)	0.97	0.87	1.24	0.95	28	-0.972	0.339
Question 4 (6.5pts)	1.16	1.40	2.57	1.43	28	-5.945	0.000**
Question 5 (3pts)	0.10	0.41	1.34	1.11	28	-7.008	0.000**
Question 6 (1pt)	0.40	0.43	0.55	0.45	28	-1.609	0.119
Question 7 (1pt)	0.10	0.31	0.34	0.48	28	-2.985	0.006*
Question 8 (1pt)	0.22	0.34	0.62	0.48	28	-2.213	0.035*

6.5.4. Part Drawings

In the intervention, Part 1 consisted of a fill-in-the-blank style part drawing of the part the students were given, similar to the Knowledge Assessment part drawing. There were 28 blanks for the students to fill out. Figure 72 shows the solution and the labeled 28 blanks for the part drawings the students were given.

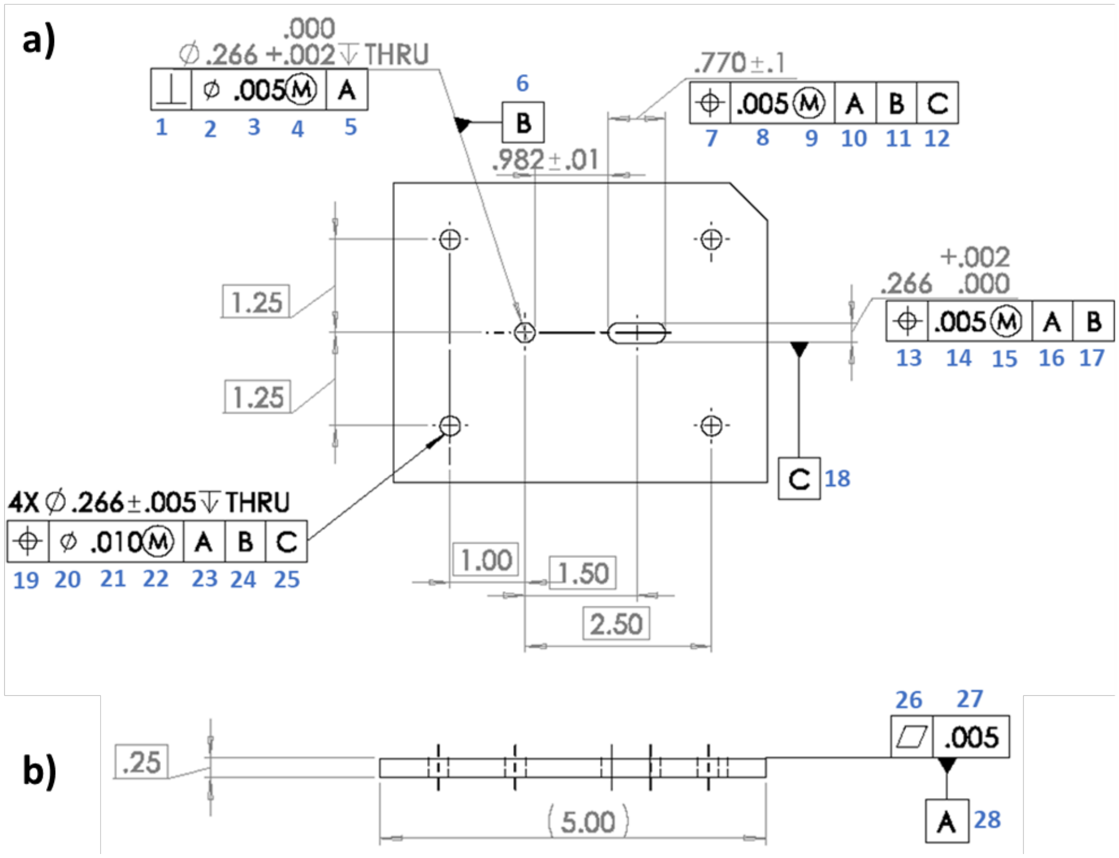


Figure 72. Activity part drawing solution of a) top view and b) front view with the labeled sections

The 28 blanks were broken into eight different topic sections. These topic sections and their corresponding blanks are broken down in Table 4. There were four topics where more than 40% of students could identify the specific blanks associated with Dimension (50.3%), Datum Callouts (41.4%), Datum Labels (48.3%), and Flatness (55.2%). The other four topics the students were not as strong in identifying the necessary characteristic callouts or labeling datums on the Activity Part 1 drawing.

Table 24. Breakdown of 8 distinct topics and their corresponding blanks on Figure 16

Topic	Related Blanks
Perpendicularity	1
Diameter	2, 20
Dimension	3, 8, 14, 21, 27
Material Condition	4, 9, 15, 22
Datum Callouts	5, 10, 11, 12, 16, 17, 23, 24, 25
Datum Labels	6, 18, 28
Position	7, 13, 19
Flatness	26

6.5.5. Exit Survey

The students were given an exit survey at the end of the intervention. The survey asked the students 5 Likert- scale questions and three open response questions. Five of the questions asked the students to agree or disagree (1 – strongly disagree and 5 – strongly agree) to if the activities contributed to the students' knowledge, and the sixth question asked the students to rate the usefulness of the overall intervention. Figure 73 shows the students' responses to the first five questions. The students mostly agreed the activities contributed to their understanding of GD&T, where Part 1 (Part Drawing) was more beneficial than Part 2 (Inspection Plan). More than half the students strongly agreed that the activities improved their knowledge of the topic. No students disagreed with the statements.

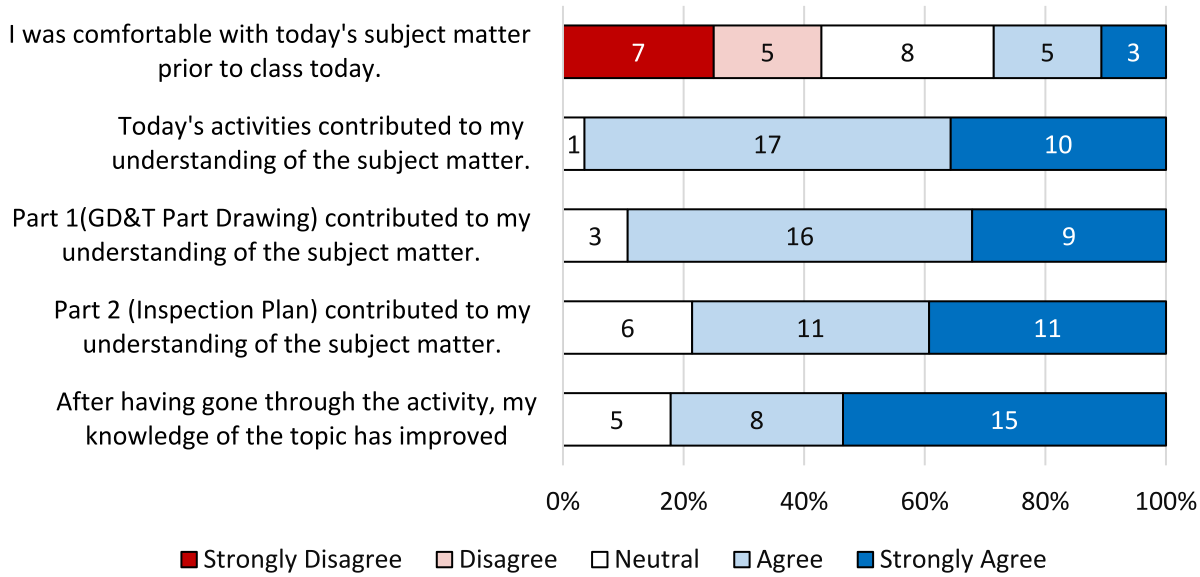


Figure 73. Exit Survey Responses

The final question for the exit survey asked the students to give an overall rating in terms of the intervention's usefulness for learning and/or understanding of the subject matter. The ratings the students were given were: Not useful at all, Slightly useful, Moderately Useful, Very Useful, Extremely Useful. No student rated the module "Not useful at all", 65% of the students believed that the activities were "Very Useful", and 8% of the students deemed the activities "Extremely Useful". The distribution of the rated usefulness shown in Figure 74 shows that over 70% of the students deemed the activities completed were wither Very Useful or Extremely Useful.

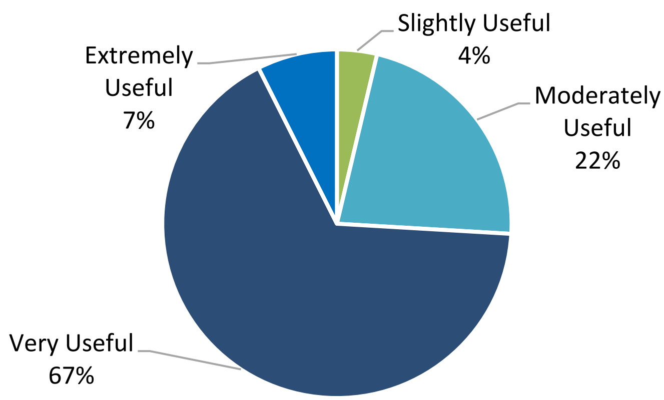


Figure 74. Distribution of the rated usefulness of the activities completed by the students.

5.7 Perceived Value Survey

The perceived value survey asked students about components that were essential to the intervention, and students indicated whether they saw value in those components. The survey is broken into two distinct parts: the role of the student and the role of the instructor. The statements "I gave the activity minimal effort" and "I rushed through the activity" were reverse coded during statistical analysis to ensure the high value of "5" was the same for every statement due to the statements being negatively worded. Regarding the role of the student, the majority of the students completely agreed they saw the value in working with a partner for the activity. Also, half of students completely agreed they saw value in working with the inspection tools and the machined parts. The distribution of the survey answers is shown in *Figure 20*.

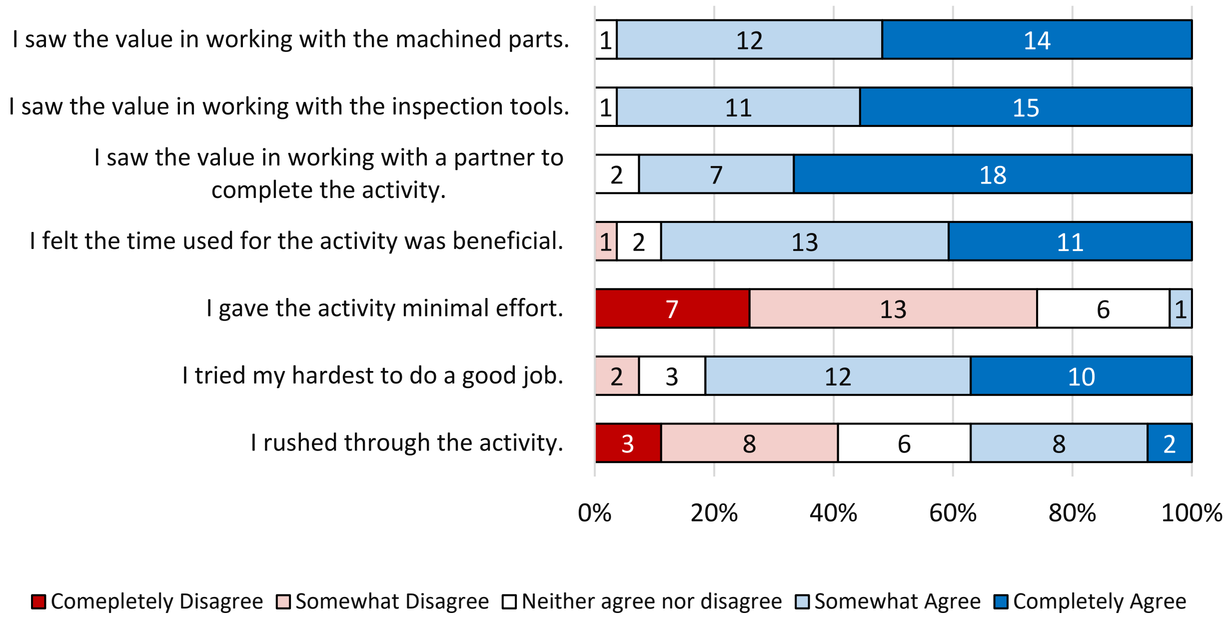


Figure 75. Perceived value survey answers in regard to the role of the students, the activity parts and their effort given.

In regard to the instructor role, the students were given statements to assess the instructor's responsibilities in the class (Figure 76). The students completely agreed that the instructors in the room walked around the room to assist if it was needed. The students, also, agreed that the instructors clearly explained the purpose of the activity and its relation to their learning. The students believed that the instructors were interactive as well as developed materials that challenged them during the learning process of GD&T.

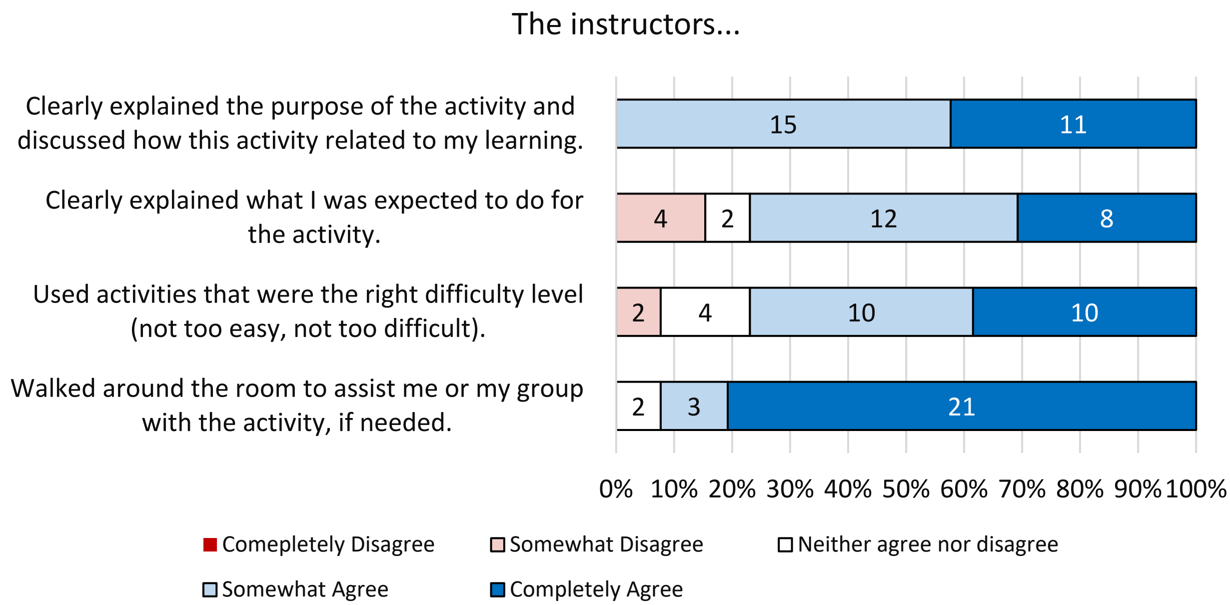


Figure 76. Perceived value survey answers regarding the instructors' roles in the activity

6.5.6. Exit Survey and Perceived Value Survey

Kendall's Tau-b correlation was run to understand the relationship between the self-reported responses on the Exit Survey and the Perceived Value survey. The data met the assumptions that it is ordinal and there is a monotonic relationship between the Exit Survey responses and the Perceived Value responses. Out of 40 possible correlations, four significant correlations resulted ($p < 0.05$). No correlations resulted from the students' perception of the instructors' role in the intervention. There is a strong, positive correlation between the activities contributing to the students' understanding of GD&T and the students not giving the activity minimal effort ($\tau_b = 0.433$, $p = 0.017$). There is a strong, positive correlation between the students reporting that the knowledge of the topic has improved after going through the activity and the three following perception survey prompts: the students not giving the activity minimal effort (τ_b = 0.414, p = 0.018); the students reporting "I tried my hardest to do a good job" (τ_b = 0.354, p = 0.044); and the students seeing the value in working with the inspection tools (τ_b = 0.447, p=0.015). These results revealed the students who gave effort to the activities also gained a sense of understanding of the topic of GD&T. Interestingly, the students who found value in working with the inspection tools noted the activities increased in their knowledgebase in GD&T.

5.9 Self Efficacy and Exit Survey

Kendall's Tau-b correlation was run to determine the relationship between 27 students' overall change in Self-Efficacy and how they believed the activities impacted their knowledge. The assumptions the data met were that is the data is ordinal and there is a monotonic relationship between the pairs of data. The difference of the Self-Efficacy scores were taken (Post-Pre) and compared to the Exit Survey questions. Out of 60 possible correlations, four significant correlations were found. There is a strong, positive correlation between the students being comfortable with the subject matter before class and their understanding of how to set up a part in a CMM (τ_b = 0.504, p = 0.001).There was a strong, positive correlation between the students' confidence in their abilities to verify the position of features using a functional gauge and the overall activities contributing to their understanding of GD&T (τ_b = 0.446, p = 0.008). There was a strong, positive correlation between the students' confidence in their abilities to verify the position of features using a functional gauge and Part 1 (Part Drawing) contributing to their understanding of GD&T (τ_b = 0.336, p = 0.043). Also, there was a strong, positive correlation between students' confidence in measuring hole position using a gauge pin, calipers, and a machinist square and Part 2 (Inspection Plan) contributing to their understanding of GD&T ($\tau_b = 0.393$, $p = 0.018$).

6.5.7. Self-Efficacy and Knowledge Assessment Scores

Kendall's Tau-b correlation was run to determine the relationship between 28 students' overall change in self-efficacy and difference in the total Pre- and Post-Intervention Knowledge Assessments. The hypothesis is there is a relationship between the difference in self-efficacy scores and the change in Knowledge Assessment scores for the GD&T activities. The assumptions the data met were that is the data is ordinal or continuous and there is a monotonic relationship between the pairs of data. Similar to the self-efficacy difference calculation, the percent change (Post-Pre) in the Pre- and Post-Intervention Knowledge Assessments total scores were calculated. Out of 15 possible correlations, one significant correlation resulted. There was a strong, positive correlation between students' confidence in measuring the flatness of a feature using the horizontal dial indicator and the percent difference in the assessment scores ($\tau_b = 0.359$, $p = 0.012$).

6.5.8. Self-Efficacy and Perceived Value Survey

Kendall's Tau-b correlation was run to understand the relationship between 27 students' overall change in self-efficacy and their perceived value of the intervention given and the instructors' role. The hypothesis is there is a positive relationship between the difference in self-efficacy scores and Perceived Value statement responses. The assumptions the data met were that is the data is ordinal and there is a monotonic relationship between the pairs of data. Out of 165, seven significant correlations were found – three in regard to students' perception and four regarding the instructors' role. There was a strong, positive correlation between the students' confidence in calculating the maximum material condition (MMC) of a specific hole and them admitting that they tried their hardest to do a good job (τ_b = 0.362, p = 0.032). This association shows that the students trying their hardest with the activity allowed them to understand how to calculate the MMC of a hole. The two other associations were strong, negative correlations between the students rushing through the activity and their confidence to choose the correct reference datum based on part description (τ_b = -0.3309, p = 0.042) and their confidence to understand how to set up a part in a CMM (τ_b = -0.426, p = 0.009). The students' self-reported abilities and their lack of rushing through the activity were correlated for the identification self-efficacy prompts. These associations show that the students who didn't rush through the activity were likely to set up a CMM and identify the datums based on given information.

For the instructors' role associations, the students' confidence in their ability to measure perpendicularity of a hole using a gauge pin and dial indicator had a strong, positive correlation with the students believing the instructors clearly explained the purpose of the activity and discussed how the activity related to their learning (τ_b =0.335, p=0.049). There was a strong, positive correlation between the students' confidence in calculating the max material condition (MMC) of a specific hole and the students believing the instructors clearly explained what was expected of them for the activity (τ_b = 0.381, p= 0.026). There was a strong, positive correlation between the students' confidence in calculating the least material condition (LMC) of a specific hole and the students believing the instructors clearly explained what was expected of them for the activity (τ_b = 0.338, p = 0.045). Also, there was a strong, positive correlation between the student's confidence in their understanding of how to set up a CMM and the students believing the instructors walked around the room to assist, if needed (τ_b = 0.400, p = 0.024). These associations of self-efficacy and the instructors' roles show that the students believed that the instructors were involved, and their involvement helped improve their confidence with certain tasks.

6.5.9. Knowledge Assessment Scores and Exit Survey Results

Kendall's Tau-b correlation was run to determine the relationship between 29 student's Exit Survey responses and the percent scored on the Pre- and Post-Intervention Knowledge Assessments, and % in change in assessment scores. The hypothesis is there is a positive relationship between the change in Knowledge assessment scores and Exit Survey statement responses. The assumptions the data met were that is the data is ordinal or continuous and there is a monotonic relationship between the pairs of data. Out of 15 correlations, one significant correlation resulted. There was a strong, positive correlation between the students' Pre-Intervention Knowledge Assessments score and how comfortable they were with the subject matter prior to class (τ_b = 0.290, p = 0.048). This association shows that the students were not comfortable, and their pre-assessment score showed similar results, by overall being low.

6.5.10. Student Feedback Comments

Students were given a qualitative, short answer portion of the Exit Survey. This short answer section asked for feedback that highlighted their feelings about the activities, the strongest features, and suggestions to improve the activities for future interventions. There was a total of 68 comments spanning four distinct categories: Active Learning, Instruction, Intervention Content, Intervention Structure. Table 25 breaks down the number of comments in the categories and their respective subcategories.

Table 25: Student comments feedback and the respective categories

Topic Category	Total Comments	Strongest Feature Comments	Suggestion Comments
Active Learning	**13**	**6**	**-**
Feelings/Confidence	7	1	-
Hands-on	3	3	-
Inspection Tools/ Machined Part	2	1	-
Machined Part	1	1	-
Instruction	**6**	**-**	**5**
Explanations	4	-	4
Instructions	2	-	1
Intervention Content	**28**	**17**	**2**
Content (Clarifying)	3	1	-
Content (Overall)	4	1	-
Part 1	2	2	-
Part 2	14	11	-
PowerPoint	5	2	2
Intervention Structure	**21**	**1**	**15**
Materials	5	1	4
Structure	3	-	3
Timing	13	-	8
Grand Total	**68**	**24**	**22**

The comments were mostly geared towards Intervention Content and Intervention Structure. Most students noted that Part 2 was the best part of the intervention. This was noted as one of the strongest features due to the interactive nature of the measuring activities. The students also noted the PowerPoint as one of the strongest features due to the information included and the way it was presented. The intervention took the information and put it into practice. This led to the students giving a positive review on how the intervention made them feel. One comment said, “The activities are memorable”.

In the Active Learning category, seven comments outlined how the students felt once the intervention was finished. These comments stated that the intervention taught them a lot because either GD&T was confusing in the past, or they knew nothing at all prior to this. One comment said "Doing helps me learn" under the strongest feature category, which is the purpose of these active learning interventions. The other comments specifically talked about how using the machined part and inspection tools were beneficial and interactive.

In the Instruction category, the students gave suggestions about how to explain the material or the directions. These comments were beneficial because it showed that the students were, at times, unsure about what they needed to do for the inspection methods. Some students noted they wanted an explanation of why the measurements were being made. This shows that the students wanted a better overall understanding of the intervention and why it was needed.

In the Intervention Structure category, timing was a huge factor to the students. They believed the amount of time allotted to complete the activities was not feasible and these were rushed. Although they felt the activities were rushed, one comment stated, "Though fast, much of the material can be easily comprehended". The students suggested more time with the inspection method portion and the equipment due to being unable to complete all of the methods the intervention incorporated. Adversely, one student suggested a shorter duration of the overall intervention schedule. The students believed the structure of the intervention would benefit them more if the sequence of the activities was changed. The students suggested the packet be rearranged to put Part 1 after Part 2 because the students understood more after the inspection plan. For the materials, the students suggested that the instructors utilize videos to demonstrate how to set up everything correctly, give paper copies of the slides/key points, and post slides about the intervention in advance to give them ample time to understand the concepts. One student believed that the materials given that showed examples of the setup process for the inspection methods was one of the strongest features.

6.6. Discussion

The activities were beneficial to the students' learning of GD&T and informative to help the instructors understand how the students were impacted. This section discusses the significance of the student feedback received through surveys and how the students faired with the intervention.

6.6.1. Student Feedback

The Exit Survey was insightful feedback to help the researchers understand if the students felt they were impacted by the activities set forth in the intervention. The majority of the students agreed that the intervention contributed to their understanding of GD&T, but at most six students were neutral about the intervention's contributions. Part 1 was more impactful than Part 2, but the students reported the intervention contributed to their understanding of the subject matter and their knowledge of GD&T had improved.

In regard to the perception survey, all students, except one, saw value in working with the machined parts and the inspection tools. They, also, saw the value in working with a partner to complete the inspection activities. This shows that the students benefit from physical parts and hands-on learning that help students visualize their work [16]. Rios conducted a similar experiment using 3D printed parts to help students understand tolerances, considering material modifier conditions, and why they matter[16]. Over 67% of the students saw value in working with the 3D printed parts. One can conclude that hands-on learning with GD&T specifically, allows students to have a deeper understanding of the concepts being taught.

6.6.2. Intervention Activities

There was an overall significant change in the student performance on their Pre- and Post-Intervention Knowledge Assessment scores. This can be attributed to a successful overall implementation of the intervention components. Although there was not a significant change between the scores of two questions in the Knowledge Assessment, it can be concluded that there was possibly an impact on the students' knowledgebase in GD&T. Question 3 was a multiple-choice answer question asking the students to accept or reject characteristics based on the information given. The students did not perform poorly on this, possibly due to the question only having two answer choices per specification. Similarly, the students did not have a distinct change in their scores from pre to post for Question 6, which asked about the difference between parallelism and flatness. Interestingly, many students had the same score or had a negative change in score from Pre- and Post-Intervention Knowledge Assessment, which implies the intervention may have confused the students in their understanding in the difference between parallelism and flatness.

Regarding Part 1: Part Drawing portion of the intervention, less than 40% of students could successfully identify the information associated with the perpendicularity, diameter, material condition, and position categories on the part drawing for this activity. For perpendicularity, the students struggled to understand where to put the characteristic symbol or did not do it at all. For diameter, although it is a simple symbol, the students possibly did not grasp that holes and slots both have diameters and these were the focus of this part drawing; thus, these key concepts could be emphasized better. Additionally, focusing on the feature control frame and its elements is important. The lecture briefly went over the feature control frame and its characteristics, but emphasizing the elements, such as the diameter symbol, the tolerance, and the material modifier for the tolerance. These are as important as understanding and calling out datums. Branoff used the student performance to understand the key missed concepts and similarly, practice was needed for identifying features with size and defining how tolerances get applied when specifying a basic dimension [55]. Although he ran a whole course with multiple deliverables, one can see that students possibly have the same problems with understanding certain GD&T concepts.

Regarding Part 2: Measuring Activity, the students were not able to complete one of the most extensive, but most important parts of the activity – measuring hole position. This phenomenon was reflected in the self-efficacy survey analysis because the Task 9 statement asking the students' confidence to measure hole position with machinist square and calipers was the only statement that did not have a significant change in score. Although, the activity was at least two hours long, the students had to become adjusted to the different measuring tools and properly combining them to effectively use them. The hole position measuring activity consisted of many strenuous calculations and multiple tools needed in order to reach the hole position. In the other inspection activities, the students were able to understand the use of the go no-go pins and functional gauge easily to accept or reject the parts. The problem lied in the first measuring activity: Inspect Flatness. The students had problems reading and translating the dial indicator measurements to paper. Also, the setup of the dial indicator was slightly complicated, and the instructors had to assist the students in the set up for many of the groups. Even though these misunderstandings occurred in both classes, the students nonetheless expressed the activities' positive impact on their knowledge and confidence in GD&T.

6.6.3. Strategies for Implementation

The development and implementation of active learning modules in GD&T have been used in entire classes, but in this paper, the intervention was conducted during a single lab section. This topic is unique because it involves students referencing materials in order to complete the activities and come to a conclusive decision, which is if the part is in spec. The following strategies for implementation are based on an active learning intervention that allows the participants to inspect and make decisions based on measurements.

1. **Develop clearer, more concise instructions.** This will reduce the ambiguity and give the students more time to do their work instead of trying to figure out what to do. To develop clearer, more concise instructions initially, the instructor or researcher could possibly run the study with participants outside of the discipline and ask what wasn't clear about the instructions. This will help determine if it is a conceptual flaw or an instructional flaw in the intervention directions.

2. **Develop videos or diagrams that students can access to help set up the inspection tools.** Videos or intuitive diagrams that will help the students assemble

inspection set ups or any similar set ups will decrease the time the student spends on set up and increase the time students work with the parts.

3. **Work with the students closely** instead of sitting and waiting for them to have a question. This helps the students want to give their best to the activities they are working on when the instructors are working with them.

4. When developing inspection methods, **pick the two or three most common and most important inspection activities** that will give the students a substantial time to experience the hands-on activity and comprehend the reasons the activity is relevant. There is a substantial benefit to students to have a specific experience with two or three activities where the information is fully comprehended, instead of having multiple inspection activities that students rush through and do not grasp what is trying to be taught.

6.6.4. Conclusions

In this paper, the topic of GD&T in the undergraduate curriculum and its incorporation into a classroom was addressed. The development process of an active learning activity using machined parts and group learning was described to help the reader see the importance of selecting topics useful to those students who will potentially utilize GD&T in the future. Creating activities that allow students to conduct manual measurements instead of using a CMM to inspect parts helps bridge the gap in knowledge between the part drawing and the actual part. Student performance metrics were obtained through a Knowledge Assessment and a Self-Efficacy Survey, and those results were analyzed. The evaluation of the metrics revealed that the activities had a positive impact on the students based on both assessments. Also, the student qualitative feedback was analyzed and broken down to help the researchers comprehend how beneficial the students deemed the intervention and suggestions for future interventions. This gives hope that the future iterations and implementations of the GD&T intervention activities will have an increased positive impact.

CHAPTER 7. CONTRIBUTIONS

The aim of this dissertation was to understand what factors of active learning interventions impact student performance, knowledge retention, and student self-efficacy. This work introduces a new way to incorporate 3D printed multi-material and machined parts into active learning interventions in undergraduate mechanical engineering classrooms. Through the development of the active learning interventions, this work has identified necessary steps needed to develop feasible and effective learning modules in certain mechanical engineering topics. These modules can help to shift from the traditional lecturing style in specific mechanical engineering topics to a more engaging, student-centered experience.

Pedagogical design is crucial to understanding the basis of the engineering intervention. The iterative development of the activities shown in Chapter 4 integrates student opinion with the instructor's teaching experience of the activities to understand what can be done to improve them. This combination of the awareness and the importance of the student voice drove design and development of these educational innovations. This research will encourage the instructors to seek the student voice while developing any curriculum, specifically active learning curriculum. The valuable aspects and contributions of the work in this dissertation to the scientific community are described below.

7.1. Contributions of Pedagogical Development Process

The pedagogical development process described in this dissertation uses observation, assessment evaluation, and technology to improve student engagement and comprehension of complex engineering topics that are valuable to their future careers. Throughout the course of the project, the modules have been carefully crafted to emphasize the content that students would find most worthwhile to their learning, while making the activities engaging and translatable to the real-world. Iterative development is beneficial because it helps the instructors improve their coursework, while targeting student achievement as an outcome.

The process of iterative development and listening to the student voice was a huge factor in this work. The students helped enhance the module experience by giving their uncensored feedback on the positive and negative aspects of the module. Translating the student feedback into actionable items led to the development of more effective in-person active learning modules. This work, hopefully, will convince instructors and researchers to ask students about their experience in the class as it progresses so the instructor can adapt to the progress of the students. This type of student feedback exchange is not normalized, yet, but it has shown to be completely beneficial to the pedagogical framework of the development of these modules.

The structure of these modules has the potential to be adapted to by current and future instructors of multiple introductory mechanical engineering courses, such as dynamics, statics, and thermodynamics. The module structure incorporates a new take on active learning activities in the classroom, while incorporating 3D hands-on models that simulate real-world structures. These modules can be used as supplementary lessons, and potentially even extend into lesson plans to replace traditional, PowerPoint-style lectures.

This work concluded in strategies and lessons learned from activity development and deployment for the mechanics of materials and geometric dimensioning and tolerancing modules.

Although there has been a multitude of active learning interventions developed and deployed, this work takes a new approach to the pedagogical method used to disseminate the theory and practical applications of mechanics of materials and geometric dimensioning and tolerancing. For the mechanics of materials modules, there were modules developed for four topics in the class. For each topic, the modules were developed with the same module framework and were shown to be effective in translating information from the theory to the practical. Many have studied active learning in mechanics of materials where everyday products were used [10, 40] to show examples of the theory and others used complex tools to make a practical tool to explain the examples of beam bending and other similar topics [59-61]. This work utilized the theory necessary to complete the specified problem and integrated that into an active learning activity with a hands-on 3D model, which served as a visual to bring the problem to life. Furthermore, all of the parts of the apparatus are low cost, sturdy and are manufacturable in a lab with a 3D printer and waterjet.

For geometric dimensioning and tolerancing, the GD&T research that has been completed in the literature has spanned a class semester [9, 16, 55, 86, 94]. This allowed these researchers to implement the necessary information for GD&T over multiple weeks, while this work was implemented in a 2-hour time span. This dissertation emphasizes the effectiveness of a GD&T intervention for those universities that don't have a complete GD&T-focused manufacturing class in their curriculum. This intervention was designed to be an engaging, yet knowledge-heavy introduction to the topic, and this research showed that it is possible to develop this type of environment in a lab section. .

7.2. Contributions of Module Deployment

The deployment of the modules revealed many effective and ineffective components that will be valuable to the researchers who plan to adopt the structures of the modules. The topics selected for research were ones for which students tend to have the most difficulty envisioning the theoretical concepts and applicability of these concepts to the real world. The modules yielded favorable student outcomes in self-efficacy assessment scores and activity acceptance.

The active learning module feedback showed that the students enjoyed the methods used to complete the work. These specialized topic modules and interventions used in the mechanics of materials and geometric dimensioning and tolerancing classrooms can be adapted and introduced to other topics in the class and other similar undergraduate classes. Although it took years to understand the impact of deployment, the activities ultimately incorporated both vital information for the students and a transferable module development framework for the researchers. Having a framework of such activities is valuable for future researchers wanting to adapt or innovate their coursework to a design methodology that is student-centered.

7.3. Challenges

Throughout the development and deployment of the mechanics of materials modules, there were numerous challenges faced. Challenges are nice to reflect on to understand what did not work as expected. One of the main challenges was time. Timing went between 50-minutes one lecture cycle and 75-minutes to the next lecture cycle. This drastically changed the amount of information the students were able to encounter, which is believed to be the cause of the students not seeing the value of the 50-minute study sessions. Another challenge is the unforeseen circumstances that occurred, which turned the initial deployment semester, Fall 2018, into a control semester.

When it comes to student outcomes, the Intervention 1 structure was initially thought to be seen as a steppingstone from the beginner concepts of the topic to the more advanced concepts. From the feedback, the students' behavior and negative feedback showed that this deployment structure was not a good idea. This was due to the lack of challenge and the guide yourself type of group activity. Another challenge in the student outcomes is the types of information obtained from the students. As the interventions evolved, the surveys given to the students changed. This was a challenge due to the inconsistent survey metrics for the first two semesters of the module deployment.

When the translation into the more advanced Intervention 3 structure was showing promise, the COVID-19 pandemic shut the study down. The last two modules for the Spring 2020 semester were never deployed but had to be deployed virtually in Fall 2020. The virtual adaptation of the modules was a challenge due to the retention. The retention was not due to the study happening, but the virtual format of the class – there were little students as the semester progressed.

For the deployment of the GD&T intervention, there was a lot of valuable information, and the students were actively trying. The intervention was long, but the students still felt rushed due to the extensiveness of the inspection methods. The students were not able to get to many of the steps, and they didn't fill in the inspection plan as expected. Also, due to the pandemic, the students were supposed to be in partners and communicate with each other about inspecting their matching parts. Instead, the pandemic led to social distancing, therefore students randomly discussed the inspection steps with the other students at their same table.

7.4. Overall Contributions

Combining active learning and collaborative group learning is powerful method to help students achieve success in the classroom. Although engineering requires working in groups, a lot of an engineer's work is completed individually. In the classroom setting, since students do not necessarily know each other, they are reluctant to work together. Incorporating these approaches into activities in engineering classrooms will boost social collaboration, peer-to-peer learning, and class participation.

In conclusion, this research will assist in the enhancement of the engineering education field and how active learning is used in mechanical engineering instruction. Mechanical engineering courses have room for innovation and interventions that will help increase the student performance. The innovation in the form of 3D printed multi-material parts and machined parts had a positive impact on students' understanding and knowledgebase. Retention of these concepts by students shows that interventions utilizing hands-on visuals amid theory being taught in lectures was successful. This research provides insight on how to cater engineering classroom activities to student success.

CHAPTER 8. LIMITATIONS

8.1. Mechanics of Materials Active Learning Modules

Limitations that arose during the iterative development of these modules and their deployments have been minimal, but notable. When deploying the modules, timing was a major issue, along with participation. In Fall 2019, the class time, which is typically 75-minutes, was reduced to 50-minutes. This led to the instructional time allotted for the modules to be reduced drastically after the class was settled upon entering. The lack of time resulted in faster shifts in the module activities and less time for the students to comprehend the information. When the Intervention 2 structure was deployed, the timing issues were partially fixed due to the removal of Activity 3. This allowed the students to spend more time with the models and allowed the instructor to go over the answers. When the 75-minute module was deployed in Spring 2020, the instructors were able to explain the problems to the students at the end of the group work, which gave the students a better understanding of the material. The class time for the Fall 2020 virtual deployment was also a 50-minute class.

Another limitation is that attendance was not mandatory in the class; therefore, student retention was a challenge during some modules resulting in inconsistent student group composition. Attendance not being mandatory adversely affected the students' desire to participate when they saw the instruction team. This led to the abrupt shift of groups if a student was alone and took time out of the overall module structure. Groups were created randomly so that the students have a set of familiar colleagues to navigate the semester modules with. When the groups shift, students could feel isolated and won't give their best effort or feel comfortable enough to speak up. Group dynamics were not a critical issue from the feedback, but it is a factor to consider in future module deployments.

In the early stages of the development of the modules, the iterative designing was very dynamic and was adapted as needed. This is a possible limitation because the students could've gotten comfortable with the structure and knew what to anticipate, and they would be more equipped for the current structure they were used to. The Fall 2019 and Fall 2020 semesters were the only semesters where the modules resulted in a drastic Intervention change. Due to the Interventions not being consistent the whole semester and across all topics, it could be said that the effectiveness of the Intervention structure was not completely measured. For the virtual deployment in Fall 2020, the change in Intervention was due to the platform and the lack of time allocated for the class by the institute.

For Fall 2020 deployment feedback, the response rate rapidly decreased as the semester progressed. The retention rate of the class was very low by the time the last two modules (Combined Loading and Beam Deflection) were deployed; therefore, there were fewer post-survey respondents and feedback. This was due to the class being solely hosted in BlueJeans and the students' declining willingness to participate in a virtual space. The overall class attendance total dropped over 50% for the regular class, and when the students found out the module activities were about to occur, more students decided to leave; this resulted in lack of participants and final feedback about their experience with the modules.

For the students' outcomes, the research team was learning as time progressed what were the best surveys to deploy in order to gain an understanding of measurable impact and how much the modules contributed to the students' knowledgebase. The surveys that were deployed in the Spring 2020 semester gave better overall view on how the students responded to the modules and if they impacted their knowledgebase than the Fall 2019 surveys. Even though the study was one of learned lessons over time, if there was a robust, set list of surveys needed, there could've been a better correlation of how the change from the Intervention 1 structure to Intervention 3 structure (in-person) enhanced student learning in the multiple topics in mechanics of materials.

During all the semester deployments, a majority, but not all, of the students were willing to work in groups. There were two or three groups each semester that did not get along and it possibly impacted how the student perceived the module(s) moving forward. Although one cannot control how students feel about working in groups, especially with strangers, there can be a system in place to help pair students so everyone can participate and have a pleasurable active learning experience.

For Spring 2020, COVID-19 shut the research study down. This halted the in-person Combined Loading and Beam Deflection modules. This did not give the study ample time to test the seemingly promising Intervention 3 structure. Although there are great results for Axial Loading and Torsion module deployments, the in-person Intervention 3 structure modules for Combined Loading and Beam Deflection would've allowed the students to gain valuable class intervention tool, and allowed the researchers to deeply understand if the impact of the module(s) was only seen in the early stages of classwork or in the later stages of the class, where topics are combined for advanced analysis of structures.

8.2. Geometric Dimensioning and Tolerancing Intervention

Development of an active learning intervention to help the students learn a specific complex topic in mechanical engineering comes with its shortfalls. The limitations of this study stem from this project being a newly implemented active learning intervention based on Geometric Dimensioning and Tolerancing. The limitations are in both the developmental phase and implementation phase of the intervention.

In the current state of industry, GD&T is done by a CMM, and manual inspection methods are lesser known and expensive. The intervention was developed as a lower cost (<$300/pp) intervention, in which key inspection steps are taken to help measure features of a part. For high-tech inspection methods, such as the CMM, variable costs are incorporated into the usage bill, and they are used in large manufacturing facilities. This makes the cost of accessibility of the inspection machinery out of reach, and students were given outdated methods for evaluating the part specifications.

For implementation, there is not a control data set because the class in which the topic was taught does not have a previously designated unit for GD&T. Although there is not a designated unit, GD&T is a topic that is needed for use throughout the entire mechanical engineering curriculum at Georgia Tech and beyond. There is not a distinct way to conduct a controlled study about what is taught in GD&T. Another limitation of this study is the lack of iterative development that will be able to be done with the activities. This is the only semester the study was run, and the data cannot shed any light on longitudinal effects of the intervention on students' ability to communicate with GD&T throughout their tenure at Georgia Tech.

During the creation of the intervention, the ideal scenario would be for the students to use partnered learning to inspect both Part A and Part B, instead of only Part B. One partner would be responsible for each inspection protocol. Unfortunately, due to the COVID-19 pandemic and school space and class rules, there was not a feasible way for people to be partnered and for the students to work on two parts. The decision to work only on Part B was based on the more diverse inspection methods that a student would be exposed to during the activity.

CHAPTER 9. CONCLUSIONS

For mechanics of materials and Geometric Dimensioning and Tolerancing, two core topics in the mechanical engineering curricula, research was conducted from the development of active learning interventions to the implementation of these interventions in the classroom to supplement learning. Student feedback was a huge factor in the iterative development of the interventions, as well as their outcomes when they participated. This dissertation outlines every step taken for both studies since inception. In this dissertation, the three following research questions were examined:

9.1. Research Question 1

In what ways can a more hands-on learning approach to teaching mechanics of materials and GD&T enable deeper student engagement and stronger retention of concepts?

In mechanics of materials, after the careful iterative development and implementation, the Intervention 3 structure of the module showed promise. During the deployment of this module structure, coupled with the participation of the research team in the class, it was observed that there was evidence of joyous engagement throughout the classroom. The retention of the students was high; therefore, it can be said that the students enjoyed working on the activities with their groups, and manipulating the 3D model. From the qualitative and quantitative feedback, there is evidence that the Intervention 3 structure contributed to a stronger retention of the concepts. This was determined through statistical analysis and comparisons of all the intervention deployments. The incorporation of the 3D models and advanced step-by-step problems helped contribute to the long-term retention of the topics because the module helped the students apply the knowledge to the next problem, (such as the exam or homework).

For the GD&T Intervention, the lessons learned from the iterative development and deployments of the mechanics of materials modules were transformed to adapt to the needs of the GD&T concepts. The structure was similar to the previously deployed mechanics of materials interventions but incorporated a machined part for hands-on learning. Along with the machined part, the inspection activity for the machined part fostered engagement and questions in the students. From the data, the activities methods, also, enhanced students' knowledge regardless of prior exposure to the topic or none at all.

9.2. Research Question 2

How can new techniques in pedagogical design be incorporated to improve student learning and foster an engaging environment in mechanical engineering classrooms?

There were a few techniques utilized in the design of the modules that helped student learning and fostered an engaging environment. The first was iterative development. Typically, modules are developed and deployed with the same structure over a period of time. Instead, the approach taken in this research was to learn from each deployment and incorporate those lessons into the next module. The lessons were learned through the external evaluations and observations the studies underwent to help paint a picture of the class environment when instruction was occurring. The last, and most important, technique that taught the researchers lessons was student feedback. Students aren't often able to voice their opinion about the classroom activities, but this dissertation outlined the importance of the student voice and the impact it made on developing the modules throughout the years. The combination of these techniques resulted in the Intervention 3 structure engaging the students and strategies for implementing the modules into other mechanical engineering undergraduate topics.

After the strategies for implementation were developed, the GD&T intervention was developed. Like the mechanics of materials intervention, the students worked with a partner to figure out the inspection activities. This collaboration and the activities showed an increase in the self-reported metrics of the students, as well as revealed how engaging the students believed the intervention was.

9.3. Research Question 3

How can 3D printing and machining technology-driven active learning modules effectively enhance student engagement and conceptual learning in mechanical engineering topics?

For the mechanics of materials interventions, 3D printing was used to bridge the gap between the theory in a traditional mechanics of materials lecture and real life examples of structures deforming. Closing this gap using 3D models helped the students with their spatial abilities by allowing them to see why a certain force is calculated a certain way. The 3D model allowed the students to visualize the deformation behavior of a structure and its boundary conditions. Throughout the semesters, the students found value in working with the 3D printed models because it helped them visualize the problem they were given.

Similar to the 3D printed models, the machined, aluminum part for the GD&T intervention was used to provide the students a physical sense of a part meeting specifications through inspection, that was once a part drawing. Having an activity in the intervention solely focused on understanding the dimensioning of the parts helped the students communicate specifications and validate whether the part met specification. During this intervention, the classroom transformed into a collaborative and engaging environment. This environment resulted in the students seeing the value in working with the part and the inspection methods.

This dissertation research confirms that two difficult mechanical engineering topics with similarly developed intervention structures were able to achieve the same goals: fostering student engagement and improving conceptual learning of the respective topics.

CHAPTER 10. FUTURE WORK

10.1. Mechanics of Materials

For the mechanics of materials project, many different module designs, 3D model designs, and topic adaptations could be created and tested – these were beyond the available time and scope of the project due to unexpected circumstances over the course of the project. In the short-term, work can be geared towards refining the current module structures and recommendations so future modules can be implemented into the classroom as a replacement or supplement to the traditional-style lectures. In order to produce a robust intervention that can be a consistent supplement to lectures in mechanics of materials, it would be beneficial to implement an open forum at the end of the class, if time allows, to ask the students in-person how the module impacted them and for suggestions about direct improvements that can be made to make the module most impactful for them. This would allow for the researchers to better grasp the information the students were not or comfortable enough to put into their feedback responses, allowing for greater understanding and explanation about the concerns students have. In the end, it will result in an enormous focus group and more insight, instead of inference, that allows the input from the student perspective of learning and instruction.

Another path that future work could take is expanding the development the modules to cover the other five topics proposed, bringing the total to nine, in the Deformable bodies class. These topics are Stress and Strain, Shear and Moment, Stresses in Beams, Mohr's Circle, and Colum Buckling. These topics are ones for which a structure can be created to explain the concepts, or it would be beneficial for the students in have extra practice in the topic due to its' complex nature. These are the main topics of the class that have many components, and problems similar to their homework and exam problems would be used for creating the content of these modules. Timing constraints are a significant obstacle for implementing nine modules into the COE 3001 course due to university scheduling, and the need to cover all of the content required by the degree accreditation board.

Working with professors of other classes to implement the modules into their classrooms after the topic is taught in full is a step towards increased deployments of the modules, as well as increased exposure of the students to the topic interventions. This would give the research team a chance to understand how the information a professor teaches, or the lecture style of the professor makes an impact on student performance and receptiveness to the activities. This step would give increased insight into if the intervention is effective for helping students conceptualize the topics, or if this research was successful due to a combination of the current experimental class student sample. Implementing in other COE 3001 classrooms would give the students a chance to engage in the class through hands-on learning – if it's not already implemented in their course syllabus.

10.2. Geometric Dimensioning and Tolerancing

For the geometric dimensioning and tolerancing project, future work consists of developing a more concrete intervention structure that will be easily transferable between classes or lab sections. Although two lab sections did have the experience of these GD&T activities, there were issues that arose and were corrected before the second lab section.

Creating a better timing schedule and a more robust set of inspection methods that are less confusing will be helpful for the effectiveness of future implementations. Testing to see if the students benefit more from completing a part drawing after the inspection activities instead of before (as done in this intervention) is an area of interest.

Once the above research is completed, implementing this intervention structure into the ME2110 lab section syllabus to help train students on GD&T methods would be optimal. Another aspect of future work is following students for the remainder of their undergraduate years after the intervention to understand if the knowledge was retained and helpful. This shed light on whether the knowledge was used in internships, in class or capstone projects, or during personal fabrication projects.

APPENDIX A. FALL 2019 AXIAL LOADING MODULE ACTIVITIES

Objectives

By the end of this session, you should be able to...

- Predict how an axial force applied will impact the structure for uniform and non-uniform cases
- Calculate force and displacements to analyze the stresses in the structures
- Create and explain axial displacement and axial force diagrams, and free body diagrams describing the loading conditions on the member
- Apply axial loading concepts to real world examples and situations

Recording Your Responses

To help us to gain an understanding of your group's overall thought process over the class period, please record your answers legibly and in an organized fashion.

Group Roles

To complete this activity your group members will need to fill the following roles:

- ❏ Experimenter
- ❏ Calculator
- ❏ Scribe

You may rotate roles throughout the class if you'd like, but please make sure there is always someone filling each role.

Materials

Your classroom set should contain the following:

- 2 prismatic bar 3D printed samples
- Apparatus to hold 3D printed samples
- Protractor with ruler

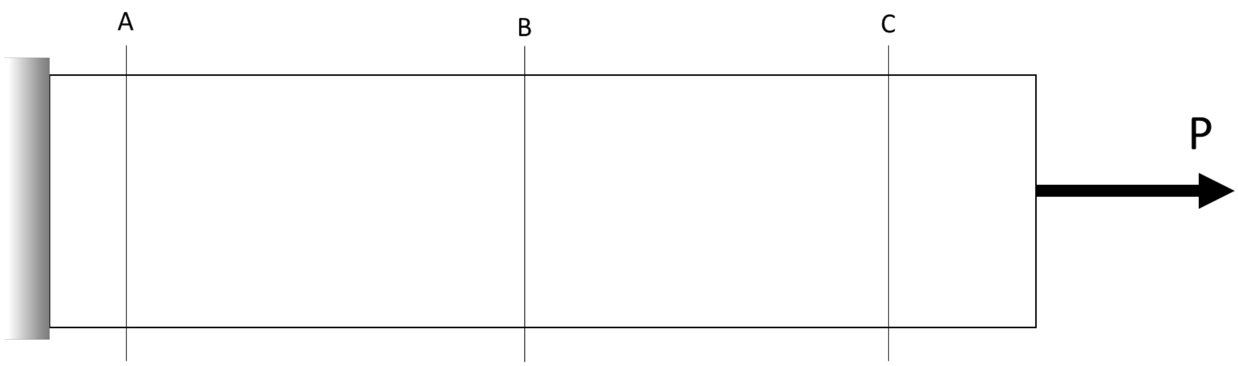
If you are missing something, please raise your hand to let us know.

Activity 1: Understanding the Basics (5 mins)

Understanding how different structures subjected to axial loads react will help you interpret how they will deform in real-life. This activity should serve as a reminder of material you have covered in class and prepare you for Activity 2.

Part 1: Understanding St. Venant's Principle

Draw an example of St. Venant's principle on the diagram supplied below. Assume the rectangular bar is fixed, with a length L, and subjected to a constant force P. Label the area with the highest stress by shading it in on the diagram below.



What do you think the stress distribution would look like at cross sections A, B and C on the diagram above? Draw in the designated spaces below.

Cross Section A	Cross Section B	Cross Section C

Activity 2: Think About It! (15 mins)

In this activity, you will begin by predicting how your prismatic bars will behave and then you will compare your predictions to the experimental values you find while manipulating your 3D printed samples.

Please show all of your work in the space provided.

Part 1: Predict

Based on the information you have about your two prismatic bars, but without testing the materials, please answer the following questions:

Material Properties:

a. What are the dimensions of the prismatic bars you have been given? Draw and label in the spaces provided below. **Draw members without the fixed support** and label their dimensions (D, L, W, H). Label where you believe each member will experience the most stress with an **X**.

Bar 1	Dimensions	Bar 2	Dimensions

b. If each bar is subjected to the same axial load, which bar do you believe will deform the most? Explain your reasoning below.

Part 2: Experiment

Set up the apparatus with the first bar's fixed end on one end and pulling mechanism on the other, as shown in the slides projected in the classroom.

Use your hand to experiment with applying axial load to one of your prismatic bars, while being careful not to break it. Follow and complete the prompts below.

When finished, talk to your neighboring group about their findings and report them in Bar 2.

Complete all answers in SI units.

	Bar 1	Bar 2
How much did the bar elongate (δ)?		
What is the normal stress in the bar after deformation (σ)?		
What is the axial strain experienced in the bar (ε)?		
What is the max possible load applied by the experimenter (P)?		

Use the calculations page supplied and show all of your work.

Part 3: Reflect (provide your responses in the space below)

a. Did the bar you predicted to deform more than the other in Part 1b reach your expectations?

b. Was there a difference in the behavior of the bars when the load was applied? If so, describe.

Activity 3: Around the world... (7 mins)

In this activity, you will relate the theoretical concept of axial loading to real world scenarios. On the next page you will see three real world examples involving axial. Take a look at your assigned scenario and discuss the following questions (recording your answers below).

Please indicate your assigned scenario (Circle one) 1 2 3

a. Where does axial loading occur in this picture? Will it need an extra force to occur?

b. Identify the structural member(s) and the load(s) acting on it.

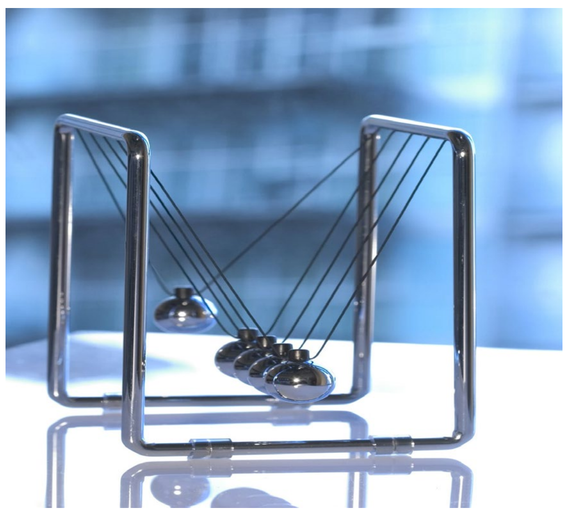
c. Is the structure you identified in tension or compression? What direction will the resulting displacement be in?

d. Draw the free body diagram to represent your scenario

If you finish early, repeat the exercise for the other two scenarios.

Scenario 1

Scenario 2



Scenario 3

APPENDIX B. FALL 2019 AXIAL LOADING KNOWLEDGE ASSESSMENT

Axial Loading

Post-Assessment

Name: ________________________________

Group Number: _________

This is a 5-minute post-assessment for the Axial Loading activity.

This assessment helps us to understand where your current knowledge stands. This assessment will not affect your grade in this course. Finish what you can, and if you don’t know something, feel free to answer to the best of your ability. Once you complete one question, please do not go back to a previous one.

You will have a 2-minute and 1-minute warning.

The answers to these questions will be shared at the end of the class period or online.

Question 1

Draw and label an example of an axially loaded member (include L, P, δ).

List 3 real world examples of axial loading.

Question 2

What is St. Venant's principle (in your own words)? Feel free to draw a diagram to help describe.

If you are given a bar uniaxially loaded like the one below, will it deform if P1=P2? If not, what will need to change in order for the bar to elongate?

Question 3

Consider a 4 m long circular bar (shown below) with a diameter of 25 cm subjected to a uniaxial load of P = 100 N, and modulus of elasticity of E = 161 MPa

a. What is the stress experienced in the bar?

b. How much will the bar elongate?

APPENDIX C. SPRING 2020 AXIAL LOADING MODULE ACTIVITES

Objectives
By the end of this session, you should be able to...

- Predict how the axial forces applied will impact a bar with varying loads
- Create free body diagrams and axial force diagrams describing the loading conditions on a bar
- Calculate force and displacements in a bar

Recording Your Responses
To help you keep notes for your exam studying process, please record your answers legibly and in an organized fashion.

Materials
Your classroom set should contain the following:

- One 3D printed sample
- Apparatus to hold 3D printed sample

If you are missing something, please raise your hand to let us know.

Activity 1: Practicing Fundamentals (15 Minutes)

Understanding how to analyze the impact of internal and external loads on bars is important for more advanced problems. This activity should serve as a reminder of material you have covered in class and prepare you for the problem in Activity 2.

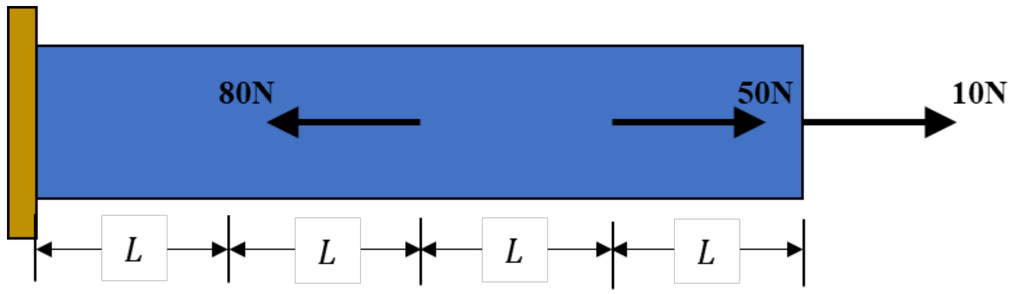
You will be asked some questions about the concepts you have been exposed to in this class thus far. Your team has been given **blue**, **green**, and **orange** cards with your team number on them. Use the space provided to work out your answers. When you've reached the answer, circle your choice on your activity packet and raise the corresponding color card.

We will go over the answers after each question is answered by all groups.

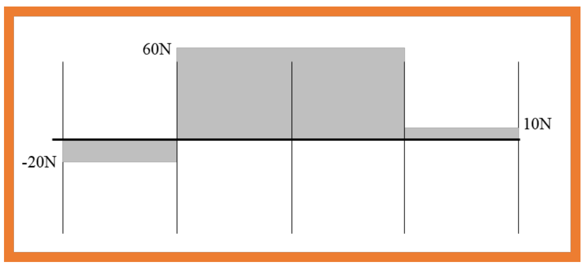
Please do not change your answer if you got it wrong originally. You will not be penalized for wrong answers.

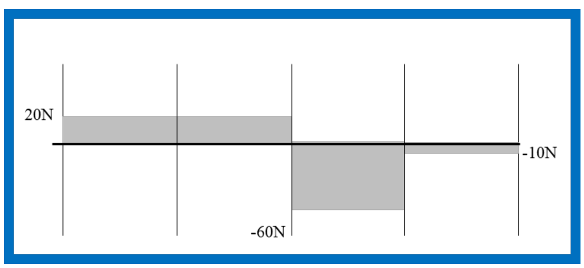
Question 1 (7 minutes)

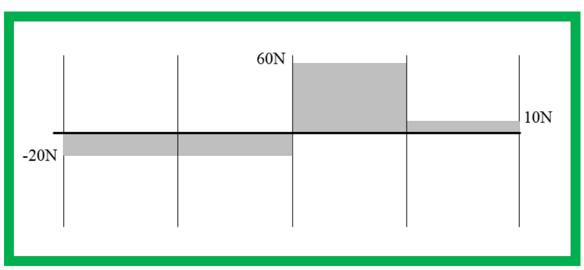
Which is the correct axial force diagram for the bar shown below?



Which answer is correct? Hold up the correspondingly colored card.

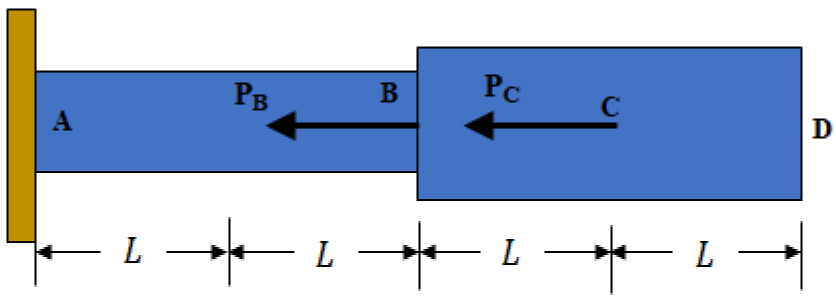






Question 2 (7 minutes)

A nonprismatic bar is loaded with a force at C. Segment AB has a square cross section and segment BD has a circular cross section with diameter D. Both segments have a Young's Modulus of E. Develop the equation for displacement, δ, of the bar at C.



Which answer is correct? Hold up the correspondingly colored card.

$$\delta = \frac{-(P_b + P_C)2L}{EA_{BC}}$$

$$\delta = \frac{-(P_b + P_C)2L}{EA_{AB}} + \frac{-P_C L}{EA_{BC}}$$

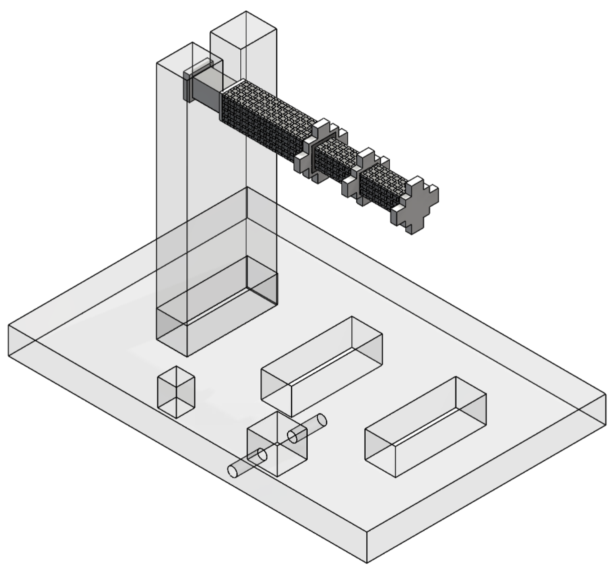
$$\delta = \frac{-(P_b + P_C)L}{EA_{BC}} + \frac{-P_C L}{EA_{CD}}$$

Activity 2

In this activity, you will be examining a bar with varying loads, which you will experiment with by assembling a physical replica. For your notes, Part 2 of this activity can be taken home to use when studying.

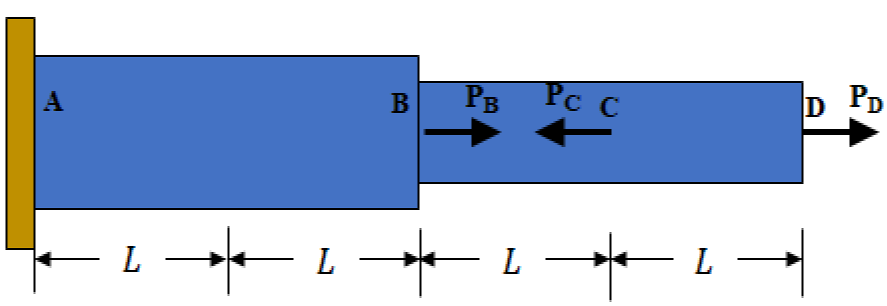
Part 1

Your group has been given a clear plastic apparatus and a 3D printed part. This set can be assembled like the bar shown below. The external tabs are for applying the external forces at points B and C.



Once set up, use the apparatus to observe the behavior of the bar when you apply the forces as shown in the figure below, where $P_C < P_D < P_B$. While observing the bar under loading, think about the boundary conditions and displacement behavior.

Does the behavior you observe in the bar under loading match what you expected to happen? If not, how was it different?

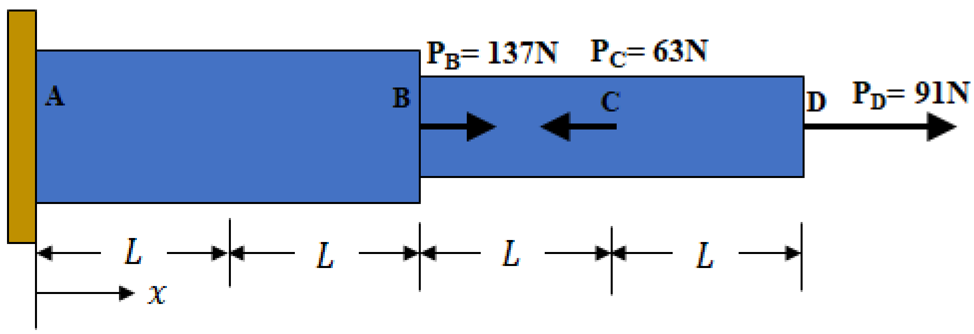


Part 2: Analyzing Internal Forces (45 minutes)

Complete the following problems for the next 25 minutes. When time is up, the instructor will work through the problems on the board, as you follow along.

A steel non prismatic bar with a Young's modulus of E=252 GPa has two sections. Section AB has a cross section of 10.2mm x 10.2mm and section BD has cross section of 7.6mm x 7.6mm.

Complete the following steps to analyze internal forces of the bar shown and plot them as a function of *x* when L= 1.90 cm.



- Develop the free body diagrams for the entire bar and individual sections showing internal axial forces in each (Sections AB, AC, and AD).

- Find the reaction forces at A.

- Find the internal axial force, N(x), for all sections (Sections AB, BC, and CD).

- Plot the axial force as a function of x.

- Find the total elongation of the bar.

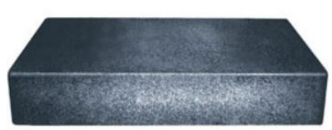
APPENDIX D. FALL 2020 GEOMETRIC DIMENSIONING AND TOLERANCING INTERVENTION ACTIVITIES

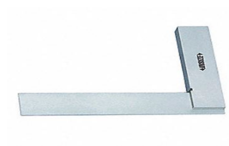
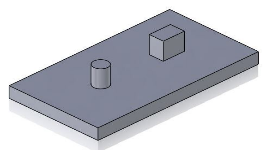
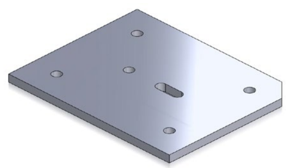
By the end of this activity, students will be able to:

- Produce GD&T part drawings to communicate part functionality to a machinist and inspector
- Demonstrate manual inspection methods of parts using GD&T information supplied
- Determine if the part should be accepted or rejected

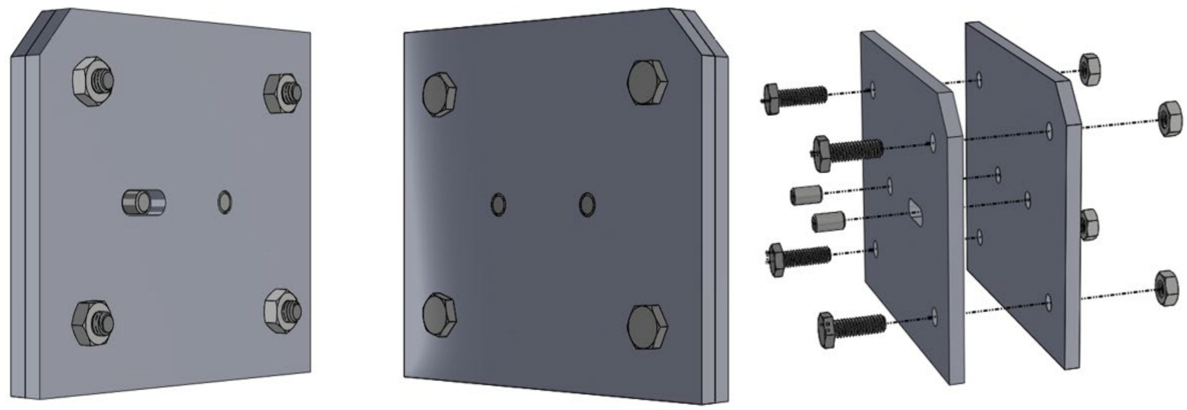
In this activity, you will be given a blank part drawing, inspection tools, and aluminum parts for inspection. If you do not have the following, please raise your hand, and let the instructors know:

Table 1: Inspection Materials

Picture of Tool/Material/Part	Name	Qty. per Set
	0.2660 in Dia. 4 in Tall Go Gauge	2
	Horizontal Dial Indicator	1
	Precision Granite Surface Plate	1
	0.2610 in Dia. 2 in Tall Go Gauge	1

	0.2710 in Dia. 2 in Tall No-Go Gauge	1
	Machinist Square	1
	Functional Gauge	1
	Part B	1
	1-2-3 Gauge Block	2

Part Description



Back View Front View Exploded View

There are two parts labeled Part A and Part B, as seen in Table 1. Part A and B are two mating plates that will be loaded in shear. A front, back, and exploded view of the two assembled plates can be seen in the diagram above.

For Part 1 of this activity, you will be must create a drawing that communicates the important features of the part to the machinist and inspector.

For Part 2 of this activity, you will act as an inspector. You will inspect Part B to see if the machinist created the part to spec based on the part drawing given to you after you complete Part 1 of the activity.

Part 1: Part Drawing

Understanding what information is vital to communication the part functionality to machinists and inspectors for manufacturing and inspection is important. The machinist must understand the part's nominal geometry and its allowable variation to help them understand what tools to use and what features to machine first.

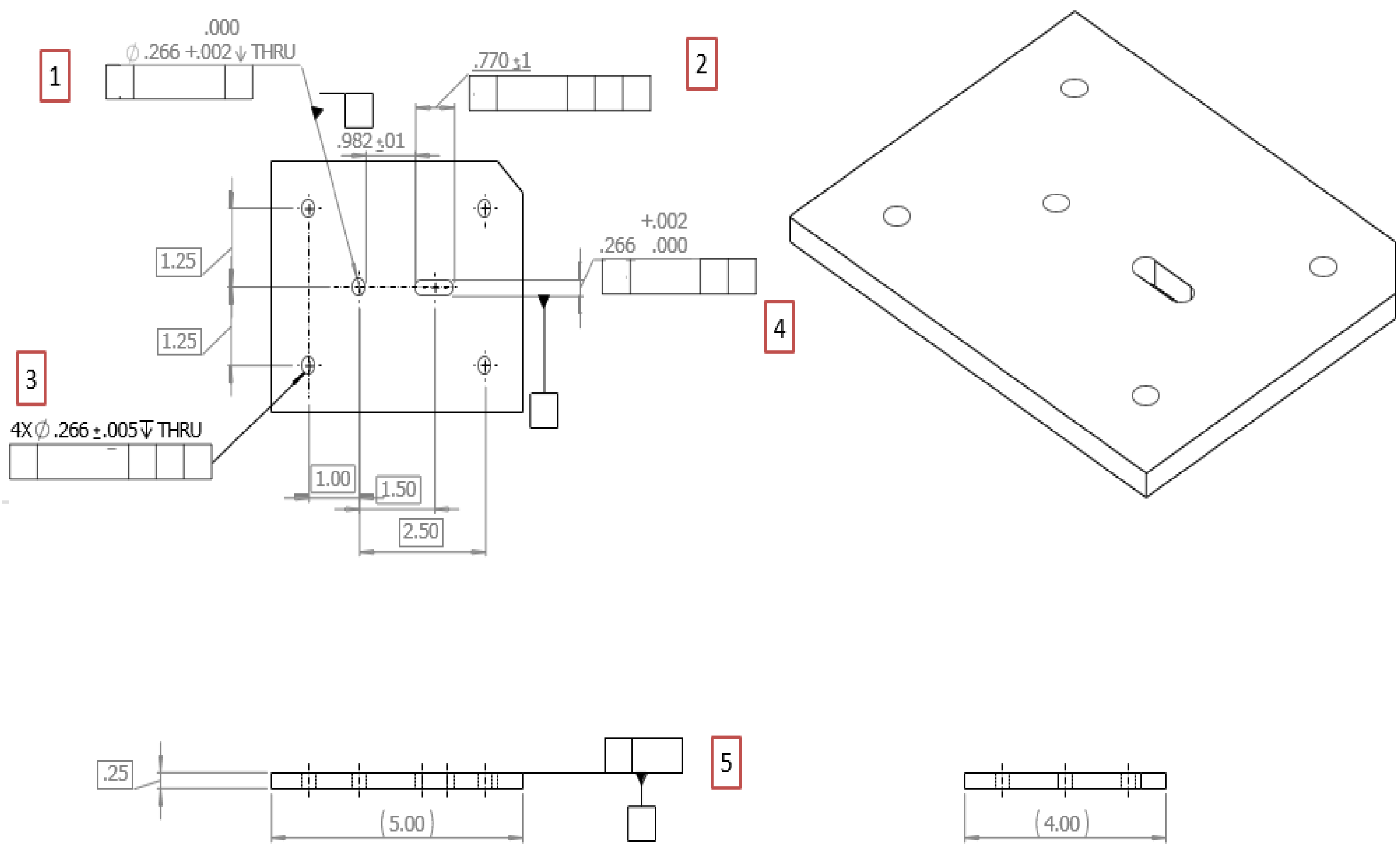
For this activity, you will be filling out the missing GD&T information in the drawing on the next page. The missing information is identified by five numbers on the part drawing. All empty boxes must be filled with the appropriate GD&T information for the necessary features outlined in the next paragraph. After filling out the missing GD&T information in the part drawing, you will show the instructor(s) the answers so that they can be documented and corrected if necessary before moving on to the inspection part of the assignment. When approved, the instructor will sign below the drawing.

Part Functionality

When creating the drawing, it is most important that the touching faces between Part A and Part B are flush (each part's flatness can only deviate plus/minus 0.0025 inches from the datum). Secondly, it is important that the two holes on the Part A align with the hole and slot on Part B, so that dowel pins can be placed into the outer 4 holes - these holes will be reamed. Lastly, the four bolt holes in the corners of Part A and Part B must be located relative to the holes and slot on both parts so that the holes align when the fasteners hold Part A and B together. The holes can vary at most 0.01 inches from the specified position. The slot position can vary at most 0.005 inches from the specified dimensions. The axis of the center hole must be perpendicular to Datum A and vary at most 0.005 inches from the specified dimension.

Please try your best to fill in:

- MMC or LMC
- Datum A
- Datum B
- Datum C
- Diameter
- Hole Position
- Perpendicularity
- Flatness



Approval Signature:

Once your drawing is seen, you are free to move on to the next Part of the activity.

Part 2: Part Inspection

Understanding the basis of inspecting different GD&T characteristics is important to understand how your part is inspected and how tolerances serve an important role in determining part's functional ability.

After your drawing from Part 1 is approved, you will use the tools listed in Table 1 to inspect Part B relative to the GD&T information in the drawing, and determine if the part should be accepted or rejected in Table 2. The inspection plan and steps are laid out in the next sections.

Use Tables 3 and 4 to record the information for the inspection of Flatness and Hole Position respectively. The measurement instructions are in the respective sections. Once completed, return to Table 2 to record the final maximum/minimum deviation, and decide if the part should be accepted or rejected.

Table 2: Part B Inspection Measurements

Feature Number	Feature	Nominal Value (in.)	Tolerance (in.)	Actual Value (in.)	Max/Min Deviation (in.)	Accept or Reject?
1	Flatness					
2	Position – Hole and Slot					
3	Slot Dimension 1 (major)					
4	Slot Dimension 2 (minor)					
5	Hole 2 Size					
6	Hole 3 Size					
7	Hole 4 Size					
8	Hole 5 Size					
9	Hole 2 Position					
10	Hole 3 Position					
11	Hole 4 Position					
12	Hole 5 Position					

Inspection Plan

I. Inspect Flatness

Use the dial indicator and two 1-2-3 gauge blocks to measure the flatness of Feature 1 shown in Figure 1. Place the dial indicator and stand on the granite slab. Place Datum A on top of the 1-2-3 gauge blocks (with Datum A facing the granite slab), as shown in Figures 2 and 3. Pick a point and calibrate Dial indicator to 0.

Sweep the surface of the part with the horizontal dial indicator and record the measured values at six points that are evenly dispersed around the part in Table 3. Determine if part passes inspection or not and report it in Table 2

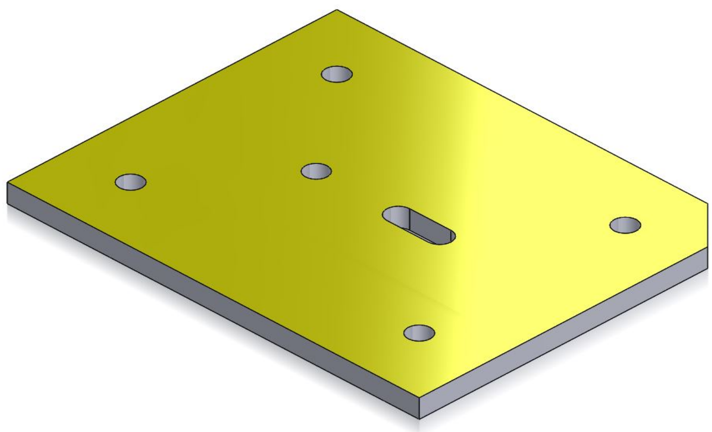


Figure 1: Feature 1 on Part B Highlighted in Yellow

Table 3: Part B Reported Values for Feature 1

Reported Values for Feature 1	
Point Measured	Deviation from Basic (in.)
1	
2	
3	
4	
5	
6	

Instrumentation Set up for Flatness Inspection

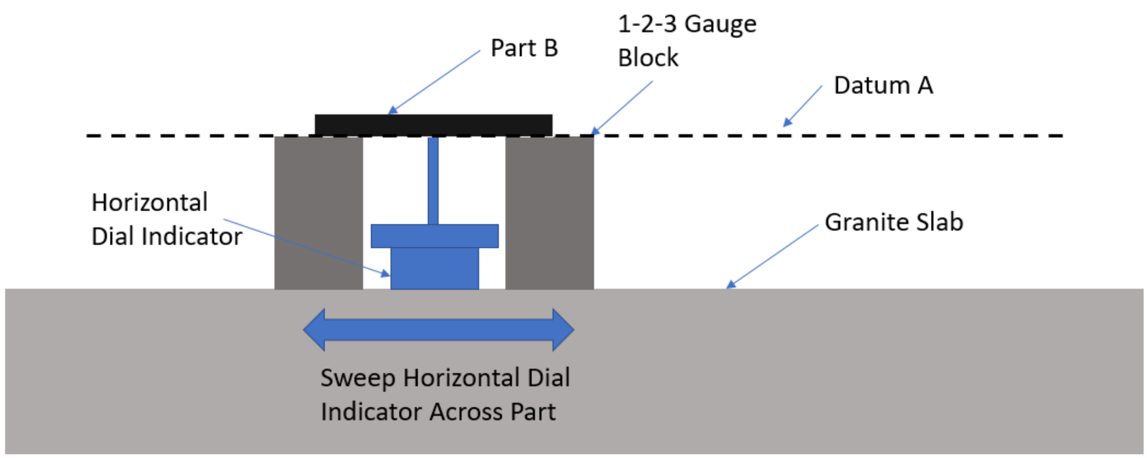


Figure 2: Measuring Flatness Set Up - Front View

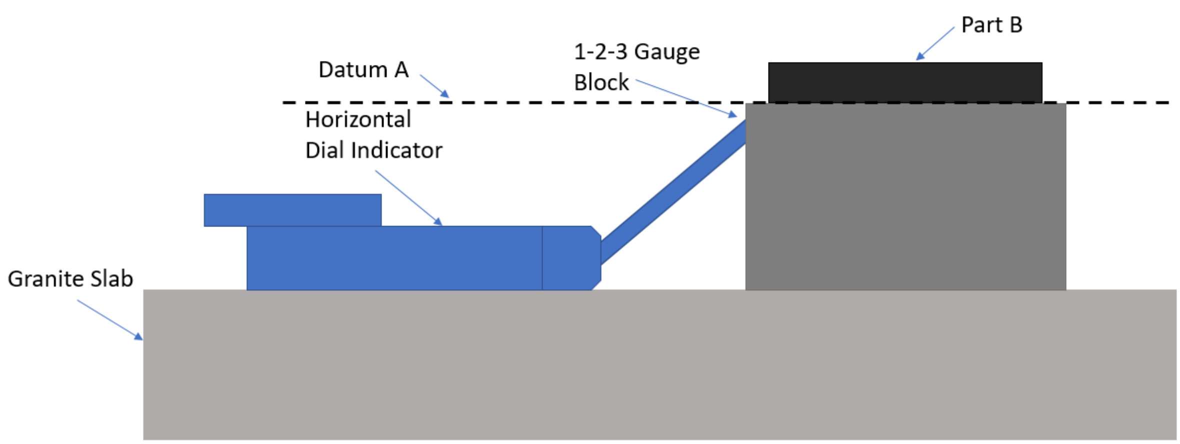


Figure 3: Measuring Flatness Set Up - Side View

II. Inspect Position of the Hole and Slot

Use a functional gauge to measure Feature 2 (shown in Figure 4) position relative to Datum C and Datum B (show in Figure 5). Datum C simulator is in green in Figure 7. Datum B simulator is in blue in Figure 7. Datum A simulator is in red pictured in Figure 7. If the Datum A simulator on the functional gauge lays flush with Datum A on Part B, and the Datum B simulator fits in the pin hole and Datum C fits in the slot hole on Part

B, then the part passes inspection. Determine if part passes inspection or not and report it in Table 2.

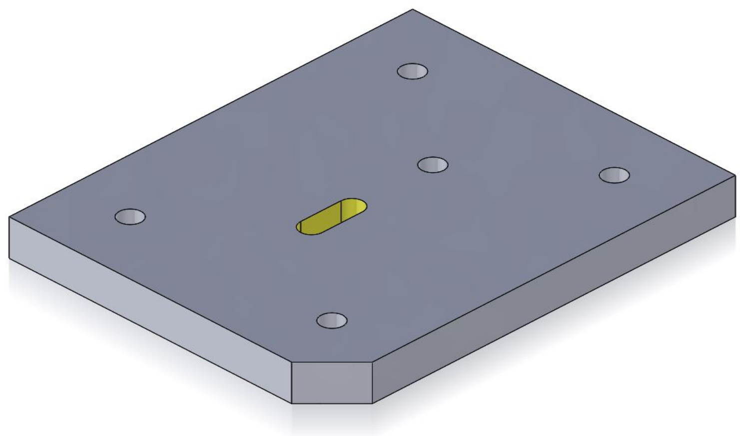


Figure 4: Feature 2 on Part B Highlighted in Yellow

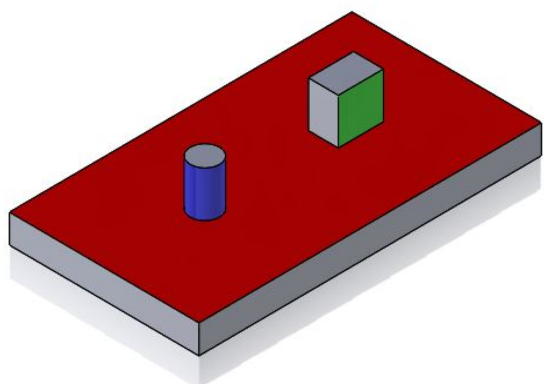


Figure 5: Functional Gauge for Part B

III. Inspect Hole Size and Slot Size and Bolt Hole Size/Position

Use a caliper to measure the major and minor dimensions of slot size (Features 3 and 4 in Table 2). Determine if part passes inspection or not and report it in Table 2

Use a “no-go” gauge pin to measure the upper tolerance of each bolt hole. Use a “go” gauge pin to measure the lower tolerance of each bolt hole (Features 5, 6, 7, 8 in Table 2). Determine if part passes inspection or not and report it in Table 2.

IV. Inspect Hole Position

Use the "go" pin and one 4 inch nominal gauge pin, calipers, functional gauge, and a machinist square (to ensure calipers are parallel to the part) to measure the "x" and "y" position of the bolt holes (Features 9, 10, 11, 12 in Table 2), as seen in Figure 6, and record measurements in Table 4, with the bolt hole numbers corresponding to Figure 6. Hole 1, as shown in Figure 7, will be used as a reference. Insert the 4in nominal pin into Hole 1 as shown in Figure 8.

Determine if part passes inspection or not and report it in Table 2.

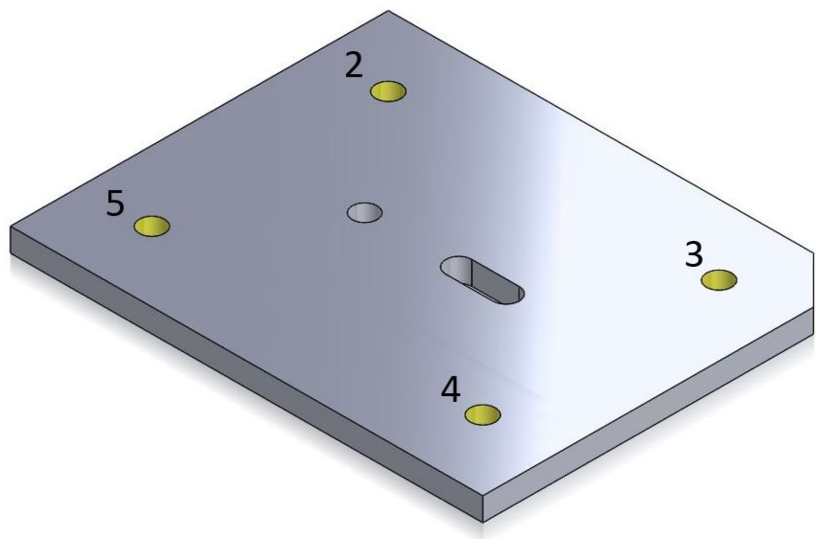


Figure 6: Part B Corresponding Bolt Hole Numbers Highlighted in Yellow

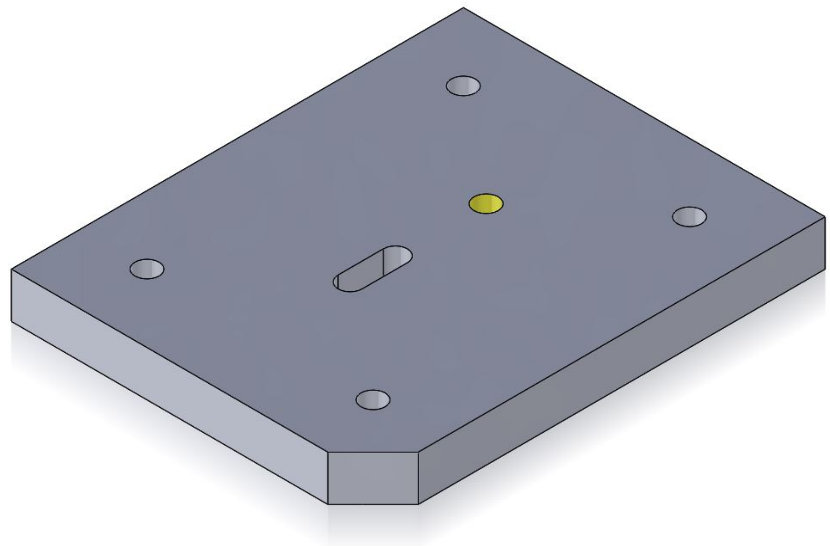


Figure 7: Hole 1 on Part B Highlighted in Yellow

Table 4: Bolt Hole Location Inspection for Part B

Hole No.	MMC Size (in.)	Actual Size (in.)	Allowed Position (in.)	"X" Deviation from Basic (in.)	"Y" Deviation from Basic (in.)	Actual Position (in.)
2		.266				
3		.269				
4		.264				
5		.262				

Instrumentation Set up for Size/Position Inspection

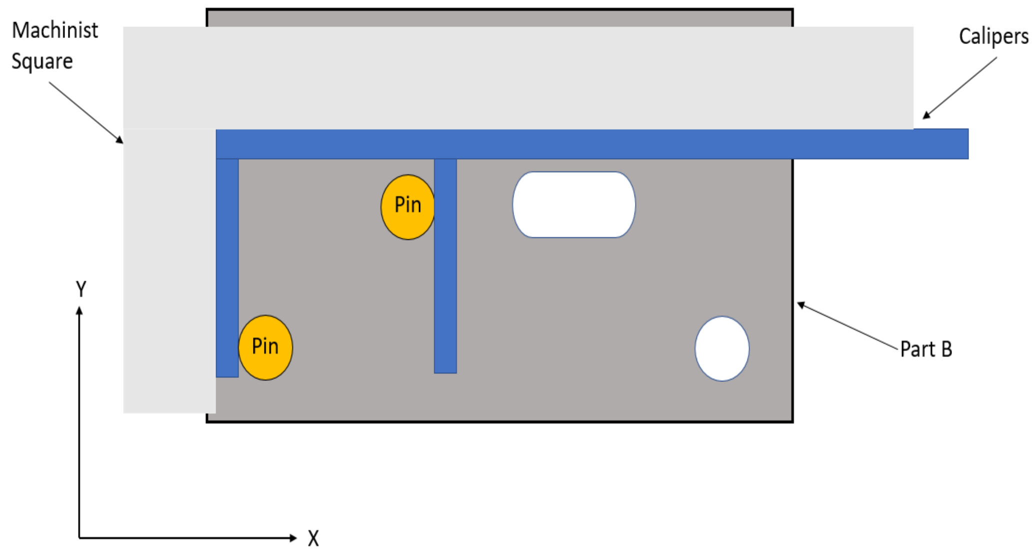
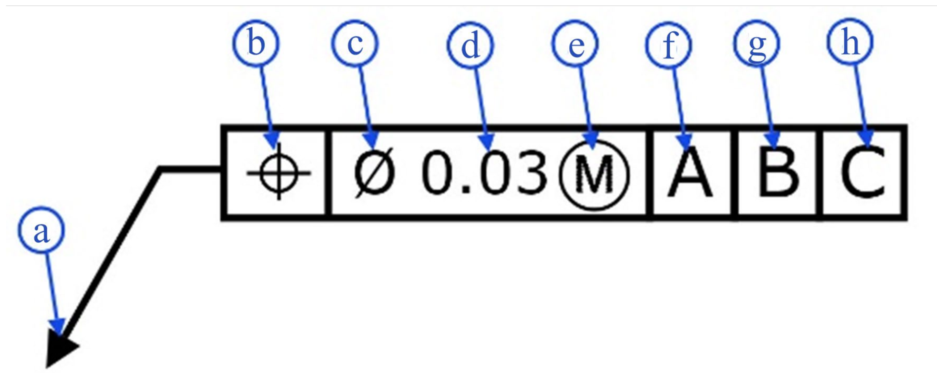


Figure 8: Set-up for Measurement using Gauge Pins, Calipers, and Machinist Square

APPENDIX E. FALL 2020 GEOMETRIC DIMENSIONING AND TOLERANCING KNOWLEDGE ASSESSMENT

1. Identify the following components of a Feature Control Frame.



a. ________________________
b. ________________________
c. ________________________
d. ________________________
e. ________________________
f. ________________________
g. ________________________
h. ________________________

2. Identify the following GD&T symbols

⏥ ______________________

⌖ ______________________

Ⓜ ______________________

⌓ ______________________

Ⓛ ______________________

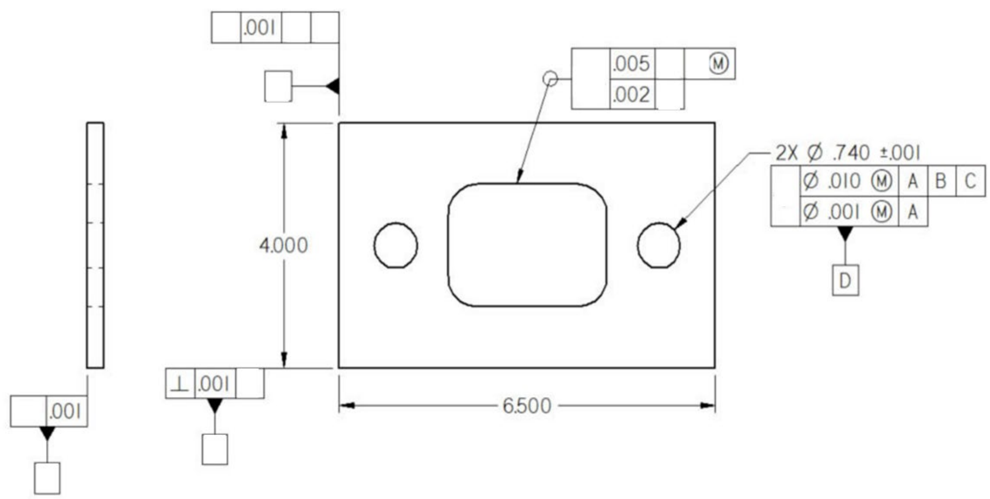
⊥ ______________________

// ______________________

3. Accept or reject the holes of a part based on the inspection characteristics in the table.

Hole	MMC Size	Actual Size	Allowed Position	X dev	Y dev	Actual Position	Accept	Reject
1	0.73	0.75	0.04	-.01	0.52	1.04		
2	0.73	0.7	0.07	.04	0.3	0.61		

4. Fill in the necessary information into the feature control frame (FCF) for the following part
   a. Establish the right-hand face in the left-side view as datum feature A.
   b. Label datum features B and C.
   c. Label the primary and secondary datums missing in the FCF.
   d. Label the GD&T characteristics for profile of surface, position, flatness, and perpendicularity.



5. To correctly identify the reference datum, what are three examples of considerations to consider?

6. Describe the difference between parallelism and flatness.

7. When using GD&T, how do machinists determine if a hole should be reamed, drilled, milled, etc.?

8. How does a Coordinate Measuring Machine (CMM) measure a part?

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