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Testing an EML Activity in Statics

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Abstract

Equilibrium of a rigid body in 3D is one of the most important, yet challenging topics for engineering students in Statics. It includes knowing supports and free-body diagrams (FBD) in 3D, having the ability to visualize vectors in 3D, and understanding moments in 3D. The concepts of moment and FBD in 3D are widely used from bridge design in civil engineering to analyzing the aerodynamic forces on plane wings in aerospace engineering. To help students understand the concepts and connect to a real-world scenario, an intuitively designed, hands-on entrepreneurial-minded learning (EML) activity was given to students to complete. Failure of a guyed antenna tower during a tornado was used as the "hook" of the activity. Additionally, a small-scale model representing the full-scale antenna tower was given to the students. The model provided the students with a physical and interactive visualization of the tower in the prompt. The combination of hands-on and real-world components contributed to the entrepreneurial mindset that the activity aimed to promote in students.

A questionnaire was sent to students who had completed the activity, aiming to gather insights into their perceptions of the effectiveness of the activity as a learning aid. The current paper provides a comprehensive description of the activity, discusses the survey questions, investigates the results, and evaluates its impact on student understanding of the equilibrium of rigid bodies in 3D.

Background

Statics is a prerequisite course in most engineering disciplines such as mechanical, civil, aeronautical, and even bioengineering [1]. The concepts introduced in the course serve as foundational knowledge for courses like Dynamics and Strength of Materials. Therefore, it is crucial for engineering educators to utilize the best strategies that enhance student learning. Danielson and Hinks investigated the perception of Statics educators on the most important Statics skills and their estimation of students' proficiency in performing the skills. A skill inventory was created using a multi-step Delphi process involving almost 20 educators. More importantly, each skill was assigned a student mastery indicator value, calculated by subtracting the average of educators' estimated proportion of students who can perform the skill from the skills' average importance value. They found that on a scale of 1-10, the skill "construct a correct free-body diagram of a 3-dimensional "real world" situation" had an average reported importance of 10 and a student mastery indicator of 2.7, showing that while it is one of the most important skills, students tend to struggle performing it [2]. The skill "Generate correct independent equations of equilibrium when given a free body diagram, i.e., trusses, frames, machines, friction, pulleys, and other situations" also had an importance score of 10 and a student mastery indicator of 2.2. Another skill highlighted was "apply force and/or moment equilibrium equations based on a correct free-body diagram", which had an importance score of 9.8 and a student mastery indicator of 2.2 [2]. The developed activity in the current study was designed to enhance these skills.

Rupe et al. explored how students make use of hands-on models in learning Statics concepts. They found that of 10 students participating in interviews after interacting with the models, "all the students used the 3D model while explaining their thinking about how values would change when one parameter is increased." They concluded that 3D models have high value in students' communication of their understanding of Statics topics [3]. Ramming and Phillips found that using hands-on labs in just the first two semesters of implementation resulted in a slight increase in homework averages and exam grades [4]. Additionally, hands-on models as learning aids in Statics are not just limited to a single topic [5]-[7]. The use of a model for the activity developed in the current paper also aims to enhance students' 3D spatial skills, which are known to be an important factor in the success of engineering students across many disciplines [8], [9].

The activity was also meant to foster entrepreneurial-minded learning (EML) and help develop the entrepreneurial mindset in students. An entrepreneurial mindset consists of three key elements: curiosity, connections, and creating value [10]. These are known as the three C's in the Kern Entrepreneurial Engineering Network (KEEN) framework. Curiosity relates to students exploring multiple perspectives in developing solutions in an ever-changing world. Connections are important when developing innovative solutions, as the ability to connect new and previous knowledge can lead to new insights. Creating value pertains to the impact that students have through their work and how it can provide value to others. A later section in this paper will provide the details on how entrepreneurial learning was considered when designing this activity, and how students reacted to it.

The Model

The model for the activity developed in the current study is shown in Figure 1. It is a customization of the Statics Modeling Kit developed by S. Ardakani and Ellis [11]. It was designed to resemble a model of the equilibrium of a rigid body in 3D. It is very simple and easy to set up yet maintains sufficient stability to remain stable throughout the students' completion of the activity. The labeled points A, B, C, and D, shown in Figure 1, are needed when students create force vectors to solve the problem, which will be outlined in the following sections. The vertical beam is placed at the origin (0,0) on the table by a ball and socket joint. Surrounding it are three pulleys, A, B, and C, with coordinates of (-3, 1, 2.5), (1, -3, 3.5), and (3, 2, 3.5), respectively. Strings are fastened to the top of the beam and rested over the three pulleys as shown in Figure 1. Mass hangers having a mass of 50g each are attached to the end of each string and masses are added to reach static equilibrium and keep the beam vertical. The total mass at points A, B, and C are 135g, 95g, and 90g, respectively. Point D, where strings connect to stabilize the beam, is located at (0, 0, 6.5).

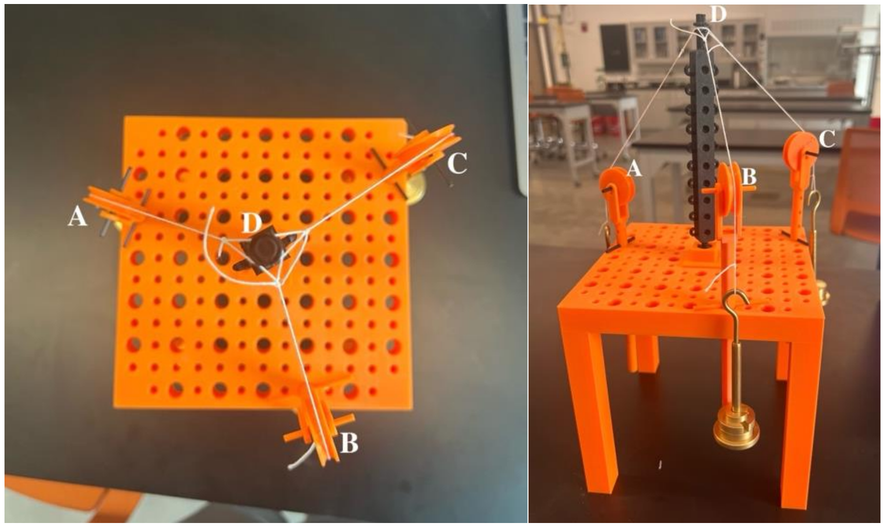

Figure 1: 3D printed activity setup

All parts needed to set up the activity except for the mass hangers and string were 3D printed on Creality Ender 3's. The time taken to print the parts ranged from a few hours for the vertical beam, pulleys, pulley shafts, and the support to just less than two days for the table. Except for the pulley shafts that were printed at 100% infill, the other parts were printed with ~20% infill [11].

The Activity Handout

A handout was created for the activity and was distributed to students in advance. The handout provided the step-by-step procedure and basic information regarding measurements and important dimensions of various 3D printed parts. For example, both images in Figure 2 were provided on the handout to show the dimensions of the table and pulleys. Generally, all holes were spaced 0.5 inches apart on the table and pulleys. The parts were designed this way so that students could easily get measurements in 0.5-inch increments [11].

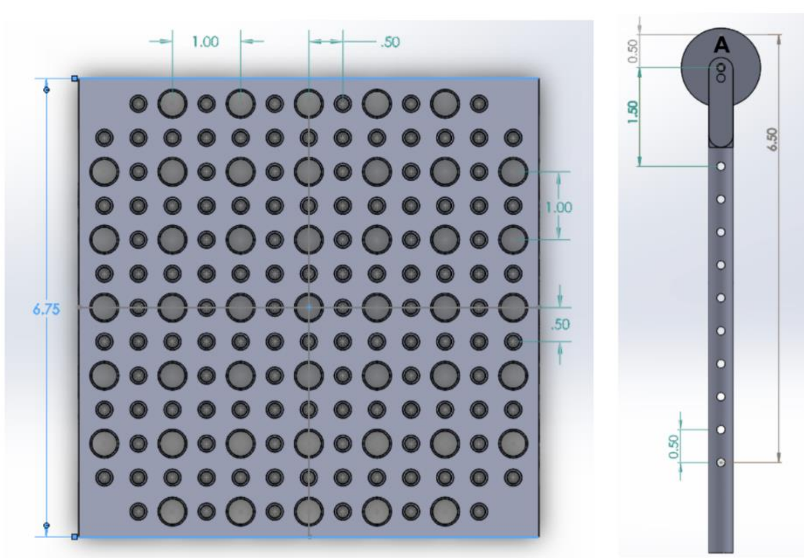

Figure 2: Images providing students with dimensions of the table and pulleys

Additionally, students were given a comprehensive prompt designed to provide a solid connection between an academic problem and a real-life scenario involving a fallen radio tower. The prompt was presented to students as follows:

In September 2017, a local radio tower in Galion, Ohio was hit by a tornado during storms on Labor Day as seen in Figure 3 [12].

Figure 3: *Radio tower in Galion, Ohio after the tornado*

Consider that you are part of the team of engineers responsible for redesigning the tower and improving the design's structural integrity while minimizing cost. Provided is a scaled-down model of the radio tower (1 inch on model = 50 feet in real life) as shown in Figure 1. The tension in the steel wires of the tower is represented by the masses hanging from the pulleys. If 100g on the pulleys corresponds to 10 kN of tension force in wires, calculate the required masses on pulleys A and C if the known total mass hanging at B is 95g. You are given three options for the wire to use. The first is a 15/32" diameter wire that has a tensile capacity of 10 kN and costs $2 per foot. The second is a 5/8" diameter wire that has a tensile capacity of 15 kN and costs $3 per foot. The third is a 3/4" diameter wire that has a tensile capacity of 20 kN and costs $4 per foot. Decide which wires are best suited for the tower and calculate the total cost of wire needed for the current setup.

The setup of the activity as shown in Figure 1, was then presented on the handout so students could see the correct orientation of the activity as well as the points A, B, C, and D clearly. Figure 4 shows the first step to solve the problem, which was to convert the mass hanging from B to the weight hanging from B in both pounds and newtons, with conversion factors given. They were then prompted to draw a free-body diagram of the 3D printed small-scaled tower.

It is worth mentioning that the activity handout was given to students as a packet, but the current paper describes each step in further detail. More space for drawing free-body diagrams and showing calculations was given in the handout itself.

Objective: Determine the tension in strings **DA** and **DC**. The coordinate of point D is (0, 0, 6.5").

Mass Hanging from B: 95 (g)

Weight hanging from B:______________________________ (N) (Hint: W = mg, g = 9.81 m/s^2)

Weight hanging from B:______________________________ (lb) (Hint: 1 lb = 4.448 N)

Draw the FBD of the small-scaled tower.

Figure 4: first steps to solving the problem, prompting students to convert units

After converting the weight hanging at pulley B and drawing the free-body diagram of the model, students were tasked with finding the tension force vectors for each string in Cartesian form. For simplicity, the students were provided the lengths of the vectors DA, DB, and DC, as well as their unit vectors as seen in Figure 5. They were prompted to find the tension force in strings DA and DC using any method. Most students chose to use vector analysis to write moment equations in 3D by forming determinants to find the unknown forces.

Express the force in each string in Cartesian form:

DA Length: 5.1 in.

Unit Vector DA, $\vec{U}_{DA} = \left\{-\frac{3}{5.1}\vec{\imath} + \frac{1}{5.1}\vec{\jmath} - \frac{4}{5.1}\vec{k}\right\}$

Force Vector DA, $\vec{T}_{DA}$:______________________________

DB Length: 4.4 in.

Unit Vector DB, $\vec{U}_{DB} = \left\{\frac{1}{4.4}\vec{\imath} - \frac{3}{4.4}\vec{\jmath} - \frac{3}{4.4}\vec{k}\right\}$

Force Vector DB, $\vec{T}_{DB}$:______________________________

DC Length: 4.7 in.

Unit Vector DC, $\vec{U}_{DC} = \left\{\frac{3}{4.7}\vec{\imath} + \frac{2}{4.7}\vec{\jmath} - \frac{3}{4.7}\vec{k}\right\}$

Force Vector DC, $\vec{T}_{DC}$:______________________________

Use any method to find the tension force in **DA** and **DC**.

Figure 5: Steps on the handout prompting students to solve for unknown force vectors

Next, Figure 6 shows that students were asked to convert their calculated tension values for DA and DC. They also had to use the conversion factor given previously to solve for the mass on the hanger that would be required for that tension. Students were then prompted to check the model and write down the actual masses used.

Calculated tension in **DA**:_______________(lb)   Calculated tension in **DC**:_______________(lb)

Calculated tension in **DA**:____ (N)

Calculated tension in **DC**:____(N)

The mass required for tension in **DA**: ____________________________________(g)

The mass required for tension in **DC**: ____________________________________(g)

Look at the mass hanging from points A and C to check your Answers.

Actual mass hanging from **A**: ____________(g)   Actual mass hanging from **C**: ____________(g)

Figure 6: Steps on the handout prompting students to find tension, the mass required for the tension, and the actual masses

Figure 7 shows that the last steps were to find what the tension forces in the strings would be in real life using the conversion factor of 100 g = 10 kN provided earlier in the handout. Once it was found, students had to choose a specific diameter of wire from the small list provided in the prompt that would satisfy the strength requirement and be cost-effective. In addition, they had to calculate the total cost of the wire needed for the new tower by multiplying the cost per foot of the chosen wire by the length of that wire needed.

Based on the actual masses hanging from pulleys, determine the forces in each wire in real life to choose the diameter of wire:
(Hint: 100g on the pulleys corresponds to 10 kN of tension force in wires)

Tension in **DA**: ___________________ (kN)   Chosen diameter of wire **DA**: ____________ (in.)

Tension in **DB**: ___________________ (kN)   Chosen diameter of wire **DB**: ____________ (in.)

Tension in **DC**: ___________________ (kN)   Chosen diameter of wire **DC**: ____________ (in.)

Determine the total cost of wires:
(Hint: 1 inch on model = 50 feet in real life)

Cost of wire **DA**: ___________________________________($)

Cost of wire **DB**: ___________________________________($)

Cost of wire **DC**: ___________________________________($)

Total cost: ______________________($)

Figure 7: Steps on the handout prompting students to determine appropriate wires and cost for their calculated tension values

Students were also given the option to complete a bonus part at the end of the handout. It was very similar to the first part of the activity, with the stipulation that, due to soil conditions and space limitations, pulley A needed to be shifted down by one inch and pulley C needed to be raised by three inches on the scaled model. If they opted to proceed, they had to reiterate the process of finding force vectors, tension forces, selecting the required wires, and recalculating the overall cost.

The Survey and Results

Shortly after the completion of the activity, a Google Forms survey was created and sent to students to gauge the activity's effectiveness as both a learning aid for the material and as a catalyst to an entrepreneurial mindset. The survey consisted of 12 questions, each based on a scale of strongly agree, agree, neutral, disagree, and strongly disagree, with corresponding numbers ranging from 1 to 5, respectively. A total of 33 responses were recorded with 19 of the participating students having completed the bonus part of the activity.

One question stated, "The small-scale model helped me visualize the problem." This question was tied with one other question for the highest percentage of "strongly agree" responses from students, at 18.18%. Slightly more than 50% of the responding students at least agreed that the model helped them visualize the problem. This indicates the effectiveness of the model as a visual aid for the prompt. Figure 8 shows the full answer distribution.

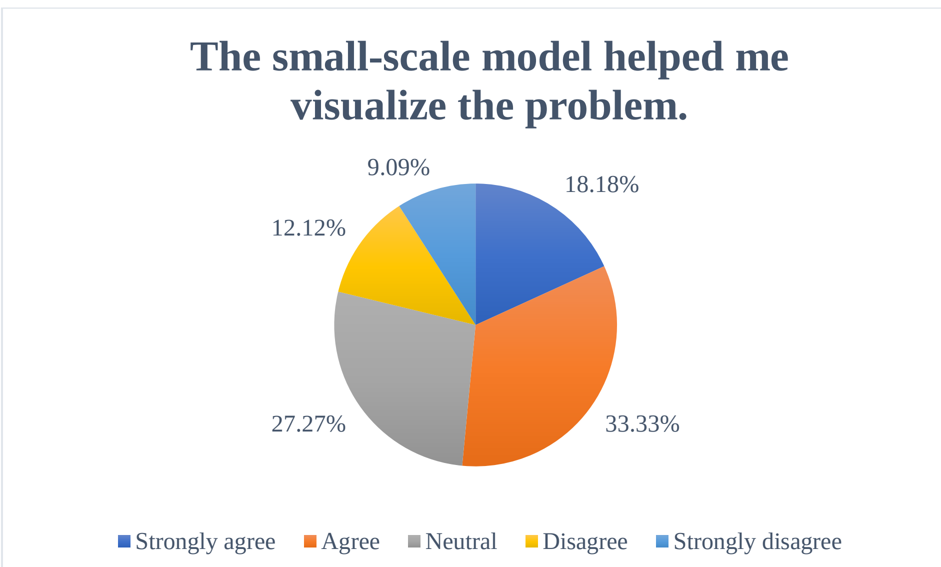

Figure 8: Answer distribution for question one

The next question was more technical, assessing how effectively the activity contributed to the understanding of moment in 3D systems. Overall, approximately 42%, or 14 students, at least agreed that the activity helped them understand moment in 3D systems. Only 27% of students disagreed, while the remaining 30% responded neutrally. Figure 9 provides a visual distribution of responses.

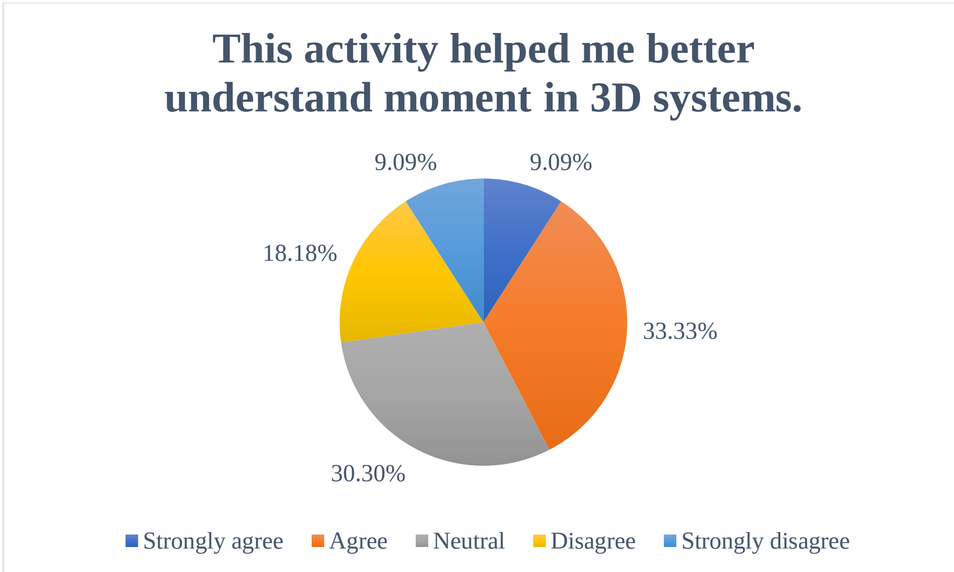

Figure 9: Answer distribution for question two

The third survey question presented a statement about students' opinions on whether the activity helped them better understand free-body diagrams in 3D. As seen in Figure 10, 9% of students strongly agreed, 36% agreed, and only a total of 27% expressed disagreement. This implies that the activity has a similar effectiveness in aiding the understanding of 3D free-body diagrams and the concept of moment in 3D.

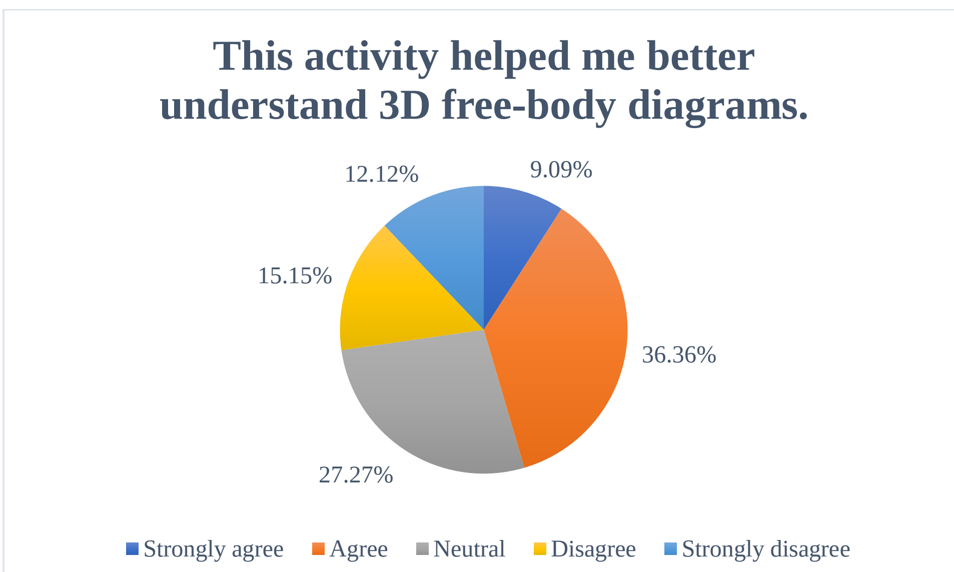

Figure 10: Answer distribution for question three

Question four of the survey focused on students' view regarding the main objective of the activity: equilibrium of a rigid body in 3D. Over 50% of students at least agreed that the activity helped them better understand 3D rigid body equilibrium, while approximately 30% disagreed in some way. This question received the highest percentage of agreed responses compared to any other question on the survey. At over 50%, this shows that the activity serves as an effective supplementary tool for students to enhance their understanding of this topic. Figure 11 provides a comprehensive distribution of responses for this question.

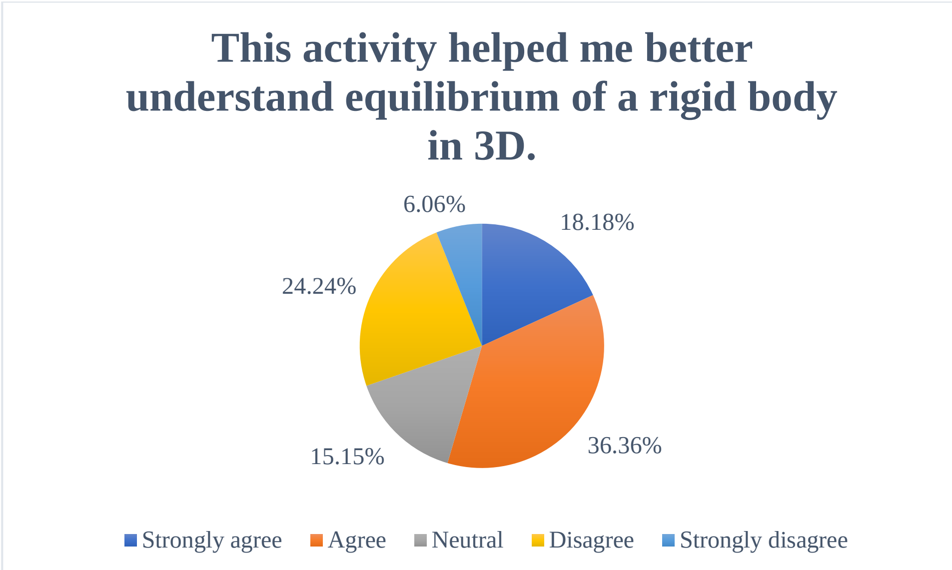

Figure 11: Answer distribution for question four

Another question inquired about students' confidence in solving real-world engineering problems. Responses were pretty spread across the board, favoring the agree side. Overall, approximately 42% of students at least agreed. It is worth noting that this question also had the second highest percentage of strongly agreed responses at 15%, right behind the two questions with 18%. Figure 12 displays the results for this question.

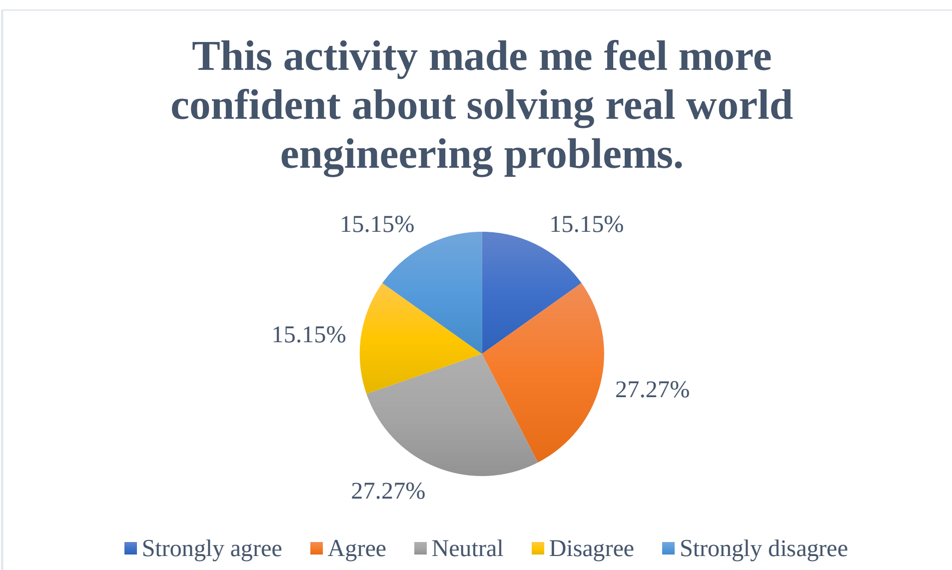

Figure 12: Answer distribution for question five

The next survey question asked if the real-world application of the activity motivated them. This question had one of the highest neutral answer percentages at 48% and one of the lowest agree/strongly agree percentages. This question did have more students agree than disagree, though. Figure 13 shows the response distribution for this question.

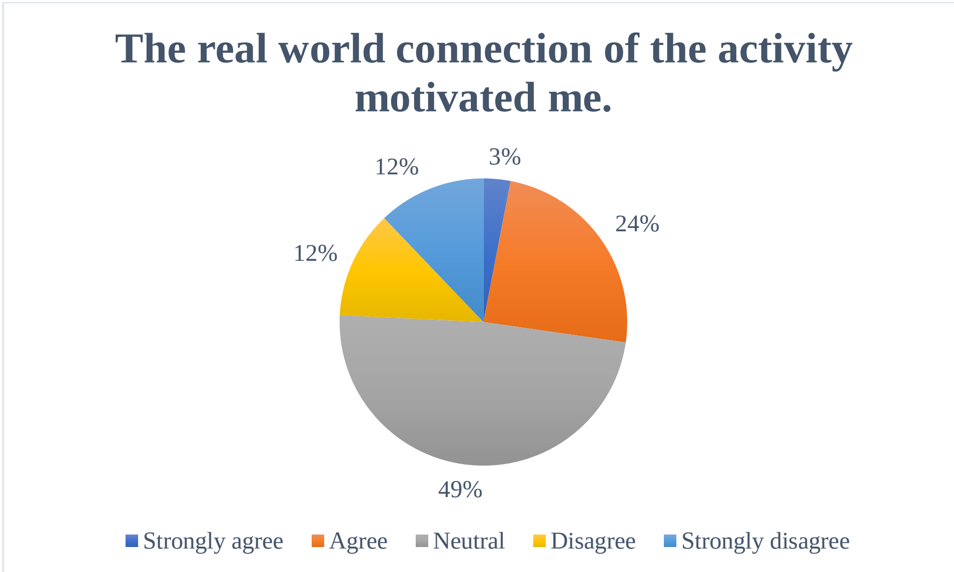

Figure 13: Answer distribution for question six

Next, students were asked whether the activity increased their curiosity about the engineering applications of Statics. This question also had a neutral response of 48%, with a slightly higher percentage in agreement than disagreement. This implies that, despite the sample size of all students, this activity may not effectively stimulated curiosity among students. Considerations on how to improve the activity will be discussed at the end of this study. Figure 14 illustrates the answer distribution for this question.

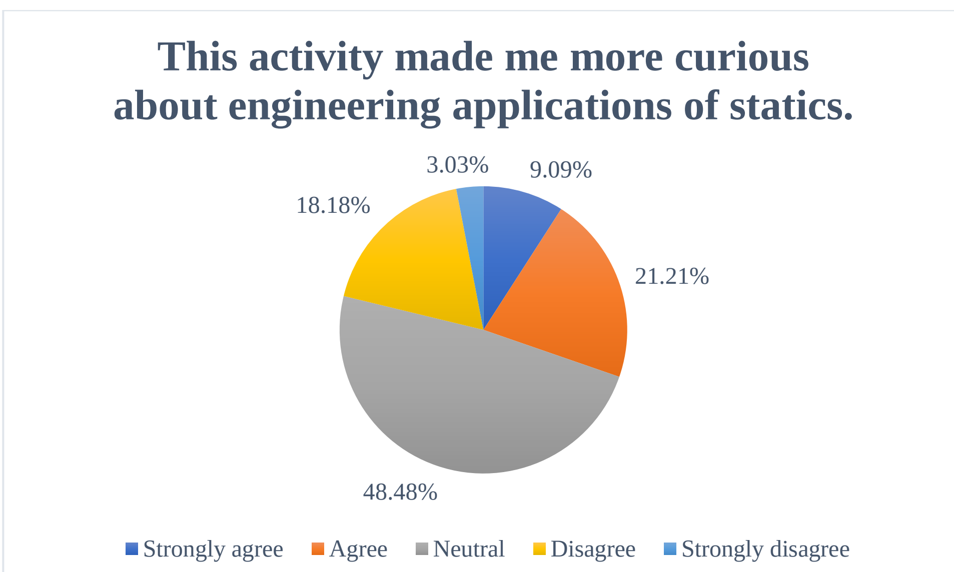

Figure 14: Answer distribution for question seven

The eighth survey question prompted students to reflect on whether the activity led them to observe more real-world applications of Statics. While 33% of students responded neutrally, nearly 40% expressed some level of agreement, compared to less than 30% who disagreed. This suggests that the activity's real-world scenario is not so abstract that students don't see any resemblance to other applications of Statics in real life. Figure 15 shows the distribution of responses for this question.

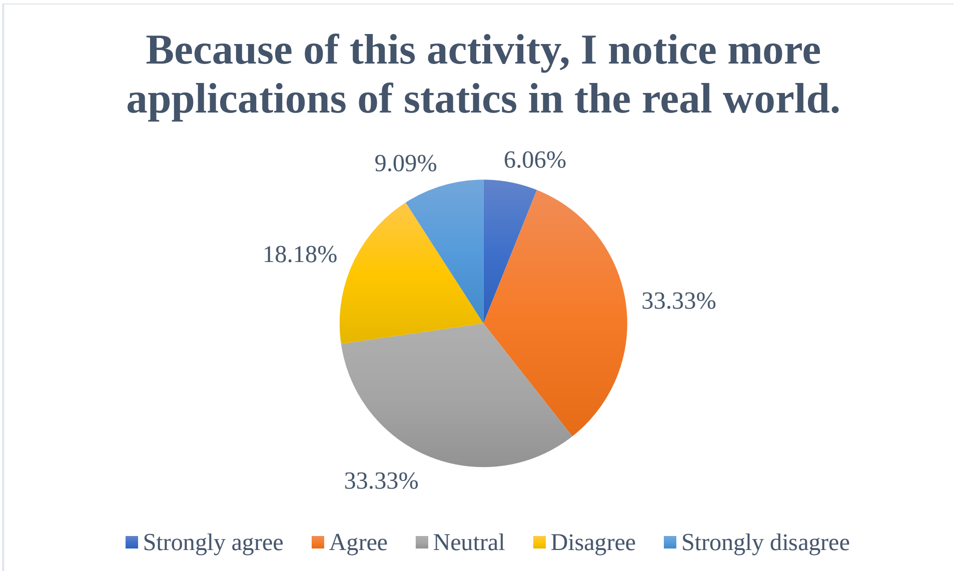

Figure 15: Answer distribution for question eight

Question nine was related to students' ownership and interest in the topic and whether the activity contributed to its enhancement. More than 50% of students responded neutrally to this prompt, indicating that the activity had limited effectiveness in increasing interest in the topic of 3D rigid body equilibrium for many students. However, approximately 30% of students indicated some level of agreement that the activity improved their interest in the topic. The distribution of responses is shown in Figure 16.

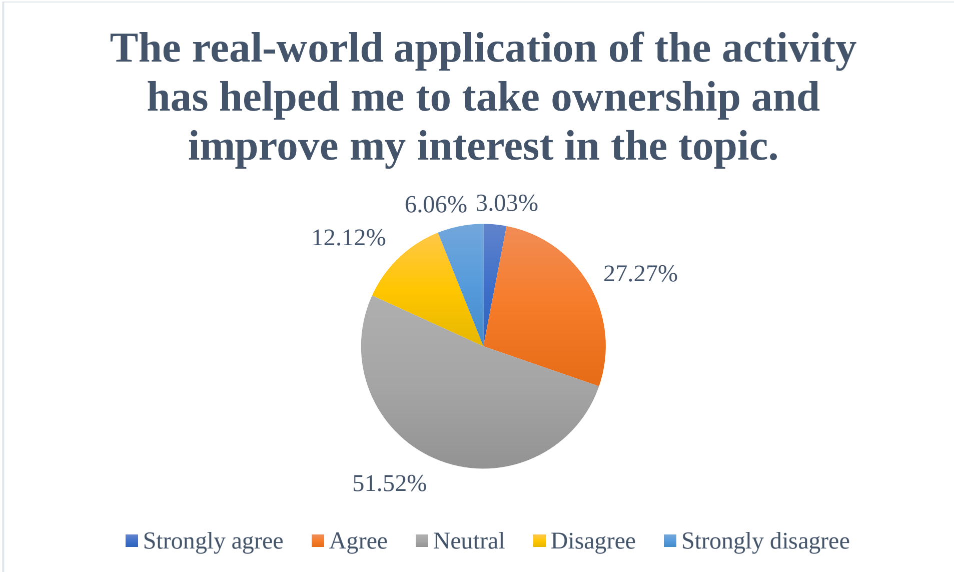

Figure 16: Answer distribution for question nine

The next survey question asked students about the activity's efficacy in enabling them to convey engineering solutions in economic terms. The activity was designed to support this objective by allowing students to select wires based on costs and to calculate the total cost of their choices. It seems the activity partially achieved this goal, as nearly 40% of students expressed some level of agreement, with only about 27% disagreed. Figure 17 shows the response distribution for this question.

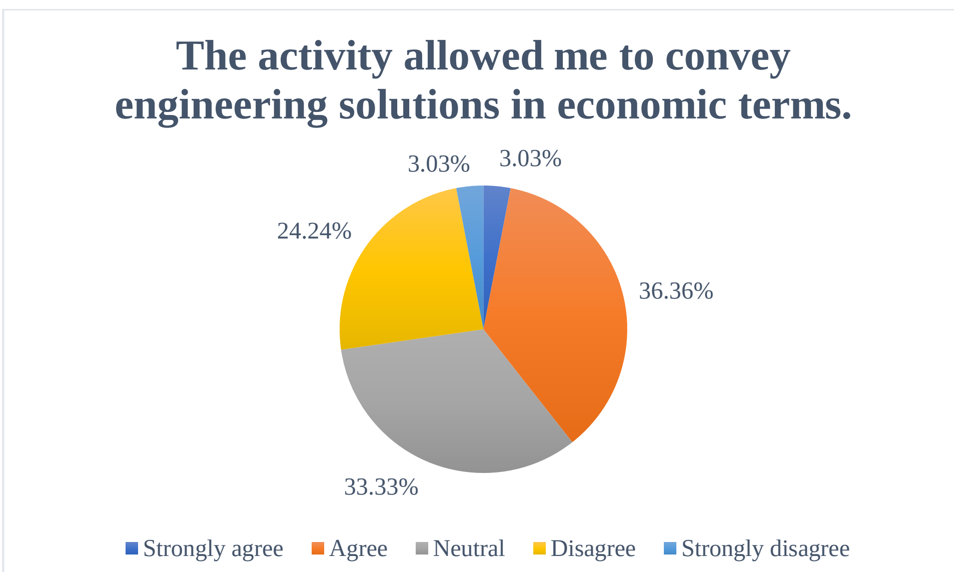

Figure 17: Answer distribution for question ten

The eleventh survey question asked about technical skills and knowledge and if the activity enabled students to utilize them in developing a solution for the client. Almost 43% of students agreed with this statement, while only about 24% disagreed. One-third of respondents remained neutral. This activity aimed to provide students with a real-world problem and the necessary information for them to not only apply their technical skills, but also exercise their best judgment when finding and presenting the solution. Figure 18 displays the distribution of responses for this question.

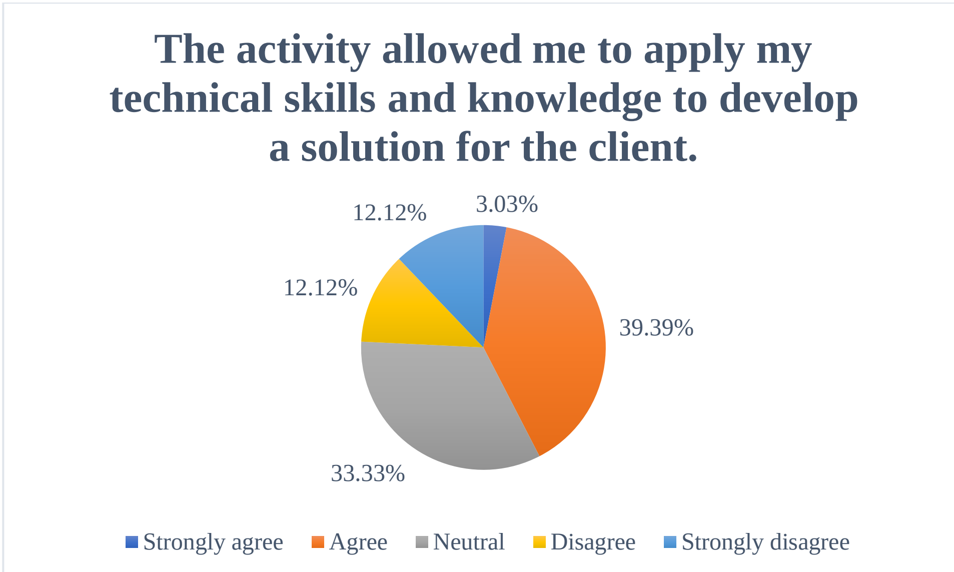

Figure 18: Answer distribution for question eleven

The last survey question was straightforward, asking students whether the activity allowed them to persist through failure. While the question was somewhat ambiguous, it provided students with the opportunity to interpret it per their own understanding. Overall, this question displayed one of the closest distributions among responses, with nearly equal representation across those who agreed, disagreed, and remained neutral. The distribution of responses is shown in Figure 19.

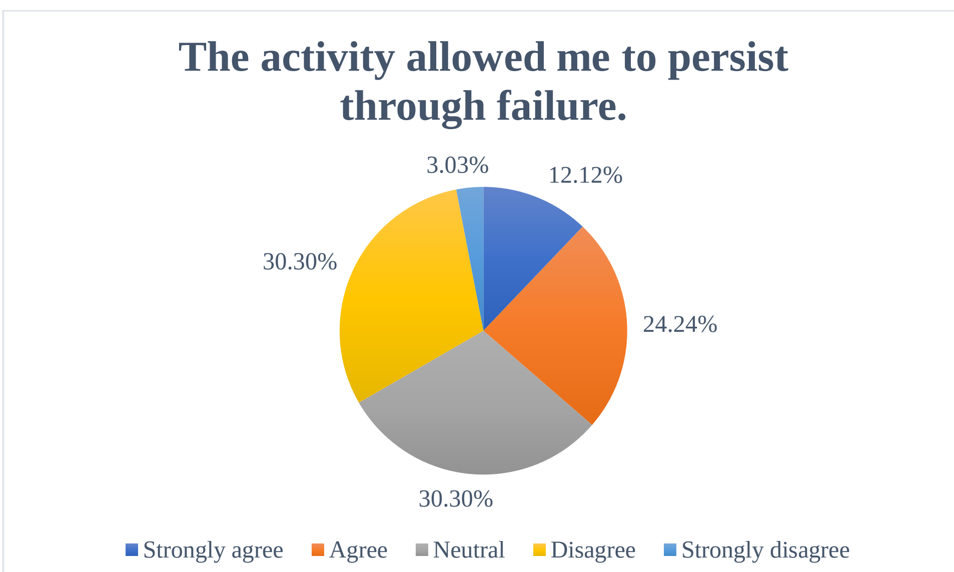

Figure 19: Answer distribution for question twelve

EML Design and Effectiveness

This activity was designed to serve as a strong example of the equilibrium of a rigid body in 3D linked to a real-world problem. This activity was the sixth in a series of seven similar activities completed throughout the semester, although, at this time, this activity was the only one with a real-world prompt. Reference [11] outlines many other activity setups that can be customized with the Statics Modeling Kit. In addition, the activity was designed to incorporate the three C's of the KEEN framework for entrepreneurial-minded learning, as previously discussed. Utilizing a real-world example for this activity was expected to address all three C's. By using an example in the real world, around 30% of responding students reported an increased curiosity about Statics applications and improved interest in the topic. Additionally, students were able to make connections from this activity, with nearly 40% of responding students agreeing that it helped them recognize more real-world applications of Statics. The last C, creating value, was included through the wording in the prompt. Framing the scenario as students being part of an engineering team tasked with improving the design of the tower not only mirrors real-world job situations, but also insists a sense of importance and tangible impact among students. Approximately 42% of responding students expressed some level of agreement that this activity made them more confident about solving real-world engineering problems. The same percentage of students acknowledged that the activity enabled them to apply their technical skills and knowledge in developing a solution for the client. The appeal to using such an approach in Statics refers back to the fact that Statics is the first technical engineering course that students take. Fostering a mindset of curiosity and confidence in students during their first major engineering course will undoubtedly benefit them when they progress to more advanced courses.

One particular step in the problem was designed to promote the economic side of entrepreneurial-minded learning. This involved presenting students with a range of wire options to solve the problem. By prompting students to consider the most cost-effective choice, they must blend their engineering skills with economic aspects, selecting wires that are adequate for the application without exceeding the necessary expenses. This exercise offers valuable exposure to students in making sound economic engineering decisions, a skillset they will utilize in their future workplaces. Allowing them to make economic decisions in a simulated environment like this offers much more room for failure than similar situations would in the real world in many cases.

Student Feedback

At the end of the survey, there were two open-ended questions asking students to share their feedback on their experience with the activity. The first asked, "What did you like about this activity?" Seven students responded that they liked the 3D model because it allowed them to visualize and interact with the problem. One student said "It brought a clearer view as to what was happening in class" and another stated "I liked how it was tangible and gave me an opportunity to see Statics and Physics help me solve a real problem, not some hypothetical questions." Some students also responded favorably to the economic aspect of the activity, with one stating "I enjoyed the connection to a real-world problem so that it seemed as though we were completing an actual engineering problem with the cost being considered." Another student stated, "I liked being able to use the solutions to calculate a real-world dollar amount that could be used to estimate the cost."

The second question asked students "What can be improved about this activity in the future?" One student responded giving the dimensions overlayed on the images provided (Figure 1 in this paper) would be an improvement. Another stated that it would be nice to have the attached weight values on the document, so they don't have to go to the engineering building just to get them in order to solve the problem. This indicated that there is no need for improvement. The measurements are easily obtainable from the model and the necessary information about unit vectors was given. One of the objectives of this activity is for students to see the model and interact with it as well as with each other. Providing them with masses will defeat the purpose.

Conclusion

It has been shown that rigid body equilibrium in 3D is one of the toughest topics for engineering students in Statics [2]. To gather further information on whether hands-on activities in conjunction with entrepreneurial-minded learning concepts help students both learn the material and adopt an entrepreneurial mindset, the current activity was designed. In addition to the 3D physical model, a prompt was created to connect the activity to a real-world scenario, giving students the opportunity to develop their technical skills and explore the economic aspects of the project.

The data found in this study is promising. The survey responses to questions one through four show that this activity is very efficacious as a classroom aid. The survey responses to several prompts related to EML were not overwhelmingly positive but still leaned towards the agreeable size. This study was conducted with voluntary feedback from 33 students out of 130 students enrolled in Statics in Fall 2023. In addition to the survey results, comparing student performance in exams would provide insight into whether the activity simplifies the learning experience for Statics students studying the equilibrium of rigid bodies in 3D.

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