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Connecting Machine Design Concepts via an Undergraduate Forensic Engineering Activity

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Abstract

A typical Machine Design course covers a myriad of mechanical elements, each with a broad set of concepts, analytical methods, and best practices—which only become more complex when assembled into an operational mechanical system. Often, the class becomes compartmentalized to focus on one mechanical element at a time. While initially effective, allowing students to target their efforts and study habits, it can be detrimental if no strong connections are built between the different learning modules at the end of the class.

This paper presents a case-study of a unique and highly engaging undergraduate Forensic Engineering Learning Activity that can be adapted and fit into any junior-level Machine Design course schedule. For three lecture sessions, a mock factory station is erected in the style of popular escape rooms, simulating the scene of an equipment failure. Students complete an initial assessment of the equipment's expected service based on a brief dossier. Small "investigation teams" are formed and granted timed access to explore the scene, collect clues, and note site safety violations. Next, students think critically about the circumstances, machinery, and human elements to compose an evidence-supported theory that identifies why the part failed and who is ultimately culpable. Findings are presented to the class, and the teams compete to convince the audience that their conclusion is correct. Instructions and recommendations for effective implementation of this learning module are provided in detail.

This activity emphasizes the critical course materials, creates connections with advanced industry topics through student-led discovery, and promotes creative problem solving. Diverse perspectives are shared between investigative team members. This case study will discuss how the activity encompassed the following skillsets: complex shaft fatigue analysis and applied failure theories, shaft features and stress concentrations, fatigue fracture surface analysis, corrosion effects, misalignment effects, manufacturing defects, motors, power, gear trains, shaft deflection, critical speed of shafts, graph and figure development, technical communication and professional presentation. This is an intensive, all-inclusive learning activity for which students have reported a great deal of enthusiasm and appreciation.

Forensic engineering classes are typically taught at the graduate level due to the multidisciplinary range of skills and knowledge. As such, it is uncommon for undergraduate students to have sufficient exposure to determine if forensic engineering is a personal area of interest. The engineering forensic investigation experience is a rare opportunity for undergraduate students to discover the oft-overlooked forensic engineering career path.

Student's have expressed enthusiasm for the learning module through favorable feedback via anonymous end-of-semester reviews. Furthermore, the engineering forensic investigation activity supports ABET Student Outcomes 1 (an ability to identify, formulate, and solve complex

engineering problems), 3 (an ability to communicate effectively), 4 (an ability to recognize ethical and professional responsibilities in engineering situations), 5 (an ability to function effectively on a team), 6 (an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions) and 7 (ability to acquire new knowledge). These outcomes are assessed via a pre- and post-activity assessment.

1. Introduction

Mechanical engineering classes typically cover a wide range of topics, and it is important to develop strong connections between the different learning modules at the end of the class. Not only does this support cross-connections and provide a holistic understanding of the material, but it also assists in reinforcing the full semester's learning outcomes for better retention. Additionally, student engagement is always a key consideration for any instructor when developing the semester curriculum, and hands-on adventurous activities are well received. For these reasons and more, escape rooms have gained popularity as an engaging educational activity across a wide range of fields [1]-[7].

An escape room is typically a fun, timed challenge where a team must explore a locked room for clues, solve puzzles, and and complete challenges in order to "escape". The features are typically themed in context of a larger narrative which often meets the genre expectations of the selected story. In addition to the fundamentals, participants strengthen their communication and leadership abilities, alongside other soft skills important for professional engineers throughout their careers [1].

There are some challenges to implementing this type of education tool, including, but not limited to, the time-consuming process of creating the room, designing and fabricating the puzzles, and the fixed nature of the solution [8]. Instructors must take care to update the room each semester to avoid the solution becoming widespread, diluting the educational benefit.

To address the typical drawbacks while maintaining the benefits, this paper presents a twist on the educational escape room structure that was developed to augment an junior-level undergraduate mechanical engineering Machine Design class. Included in the Forensic Investigation Activity was a constructed factory scene, failed equipment, hidden clues, and a coordinated story to contextualize the experience with human elements from industry. The setup was specifically designed to allow for solution flexibility from semester to semester in order to keep the experience fresh for incoming students.

This activity also provides undergraduate engineering students with a rare opportunity to gain exposure to an oft-overlooked career path. Forensic engineering courses are typically taught at the graduate level (primarily in civil engineering departments) with focus placed upon facilities and transportation failures [9]. However, evidence-based investigation is just as important as the engineering analysis. A forensic engineer must be proficient at the scientific method and engineering analysis, deducting/inductive reasoning, logic-based theorizing, and the ability to organize and communicate facts and observations [10]. The Forensic Investigation Activity presented in this paper provides an immersive experience that provides undergraduate engineer students the chance to flavor this career path while developing those skills that are not necessarily emphasized in other parts of the undergraduate curriculum.

2. Lesson design overview

The Forensic Investigation Activity progresses in three stages: Preliminary Analysis, Investigation, and Presentation. Each stage can be as broad or as in-depth as desired with some customization. These stages provide students with hands-on experience including, but not limited to, data collection/analysis, service life estimation, observation/critical thinking, and technical presentations.

The first stage is focused upon receiving the “intel” (scenario prompt) of the staged scenario. Depending upon the customization, this includes, but is not limited to, an equipment overview, assembly and component geometries, product information, loading and usage, production scale, etc. Students perform an initial analysis upon the equipment assembly and determine if the reported design information adheres to typical design practices.

The second stage is the investigation of the staged equipment failure (i.e. escape room). The students are allowed to investigate the scene of equipment failure, search for clues, and build theories as to the source of that failure. Customization of this stage can range between a fully immersive experience and an on-paper investigation.

The third and final stage requires the students to come to an evidence-based solution and present their theory in a clear and cohesive presentation. Customization of this stage can range anywhere from a competitive debate to a written report. This is a particularly beneficial exercise in technical presentation and communication because the presented solution is so specific to the student’s own logic—there must be clarity, content, *and* persuasion.

2.1 Lesson progression with examples and learning outcomes

Phase 1: Preliminary Analysis. A buffing wheel assembly is analyzed during an in-class workshop. Students measure the components of the equipment, including the shaft, buffing wheel, gear, bearings, and features (retaining rings, spring pins, gib head key). Additionally, they will learn to navigate product catalogs to identify and obtain specs for the ball bearings, which are ensconced within capped pillow blocks. Once students have taken the full measure of things, they must apply appropriate simplifications/boundary conditions to perform a fatigue analysis. The expected service life of the shaft is estimated (confirming that the reported shaft design is sufficient) in preparation for the imminent investigation. A sample assembly for this phase is provided in Figure 1, and a summary of the educational topics are presented in Table 1. Phase 1 can be conducted as an individual effort or a team endeavor.

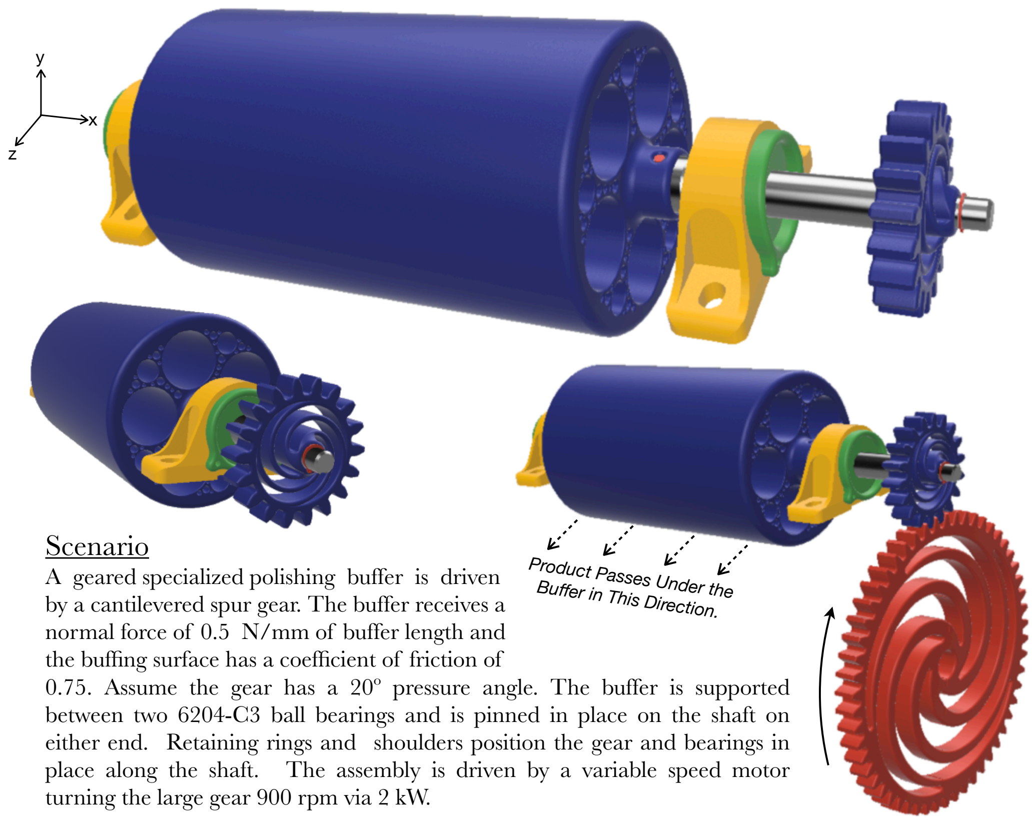

Figure 1: Phase 1 Sample Assembly Setup. While the components are obviously 3D-printed plastic for ease and speed of course fabrication, students are provided with a list of the materials the plastic components simulate

Opportunities for customization: To deepen the lesson for greater experience, consider including a CAD modeling/FEA exercise to estimate information such as deflection (which affects critical shaft speed) and or critical location/element and the corresponding effective stress state. To broaden the lesson and reduce time requirements, the instructor may consider providing the preliminary analysis results to the students as part of the introductory materials. This option is best for classes that cannot dedicate three full sessions to this activity. The customization can be scaled between the two options to suit the instructors needs/preferences.

Phase 1, in the form presented in this publication, supports ABET Student Learning Outcomes 1 (identify, formulate, and solve complex engineering problems), 5 (function effectively on a team), and 7 (acquire and apply new knowledge) [11].

Phase 2: Investigation. Students are divided into investigation teams and are allotted an amount of time in the Investigation Room where they may observe the scene of the failed equipment. Ten minutes is typically sufficient for the team to search the room, photograph clues, and begin their discussions. During high enrollment semesters, as little as seven minutes was utilized and found sufficient. Time requirements will, naturally, depend upon the complexity of the room and the numerousness of clues.

Table 1: Summary of Phase 1 Technical Lessons.

Assembly Component	Feature	Measurement/Educational Point
Shaft	Retaining Ring Grooves	Flat-bottom groove stress concentration factors.
	Shoulders	Step shaft stress concentration factors, component seating idealization.
	Keyway	Keyway stress concentration factors.
	Through Holes	Through hole stress concentration factors.
	Stress Relief Features	Compare and contrast the pros and cons of two different stress relief methods.
	Material	Fatigue analysis, factor of safety, service life estimation, material properties, failure theory selection and application.
Spur Gear	Crowned Teeth	Addendum, dedendum, pressure angle, pitch diameter, diametral pitch, thickness, seating idealization.
	Keyway	Gib head machine key analysis, factor of safety.
Ball Bearings Seated Within Pillow Blocks	Serial Number	Race width, interior and exterior diameter, outer ring edge radius with respect to shaft shoulder fillet radius, seating idealization, product identification, catalog search.
Buffing Wheel	Spring Pins	Component operation.
	Sleeves	Coefficient of friction impact upon torsional shear stress and bending stress, contact geometry (buffing wheel contact with product) versus sleeve geometry (component contact with shaft).

Photographs of a sample room scenario is presented in Figure 2. This setup was erected in a small office that had been rearranged to represent an assembly line and workspace. The scene is comprised of a several areas of interest, the first being the buffing wheel assembly. A mock conveyor system is erected such that the product (the wooden blocks) are received when they fall down a black chute from the ceiling (which flows from another area in the "factory"), and are moved under the buffing wheel into the quality assurance section (orange rollers). A small station in front of the orange rollers provides the imaginary personnel with gloves, product packaging, invoices on a clipboard, and a reject bin.

On the other side of the conveyor belt is the motor and gearing, a storage area beneath the table, and small workstation. The workstation demonstrates that tools are out and about during the maintenance period, a rudimentary weekly schedule and task list, a message board, and drawers containing work logs, spare parts, and bearing grease. The motor itself provides a serial number

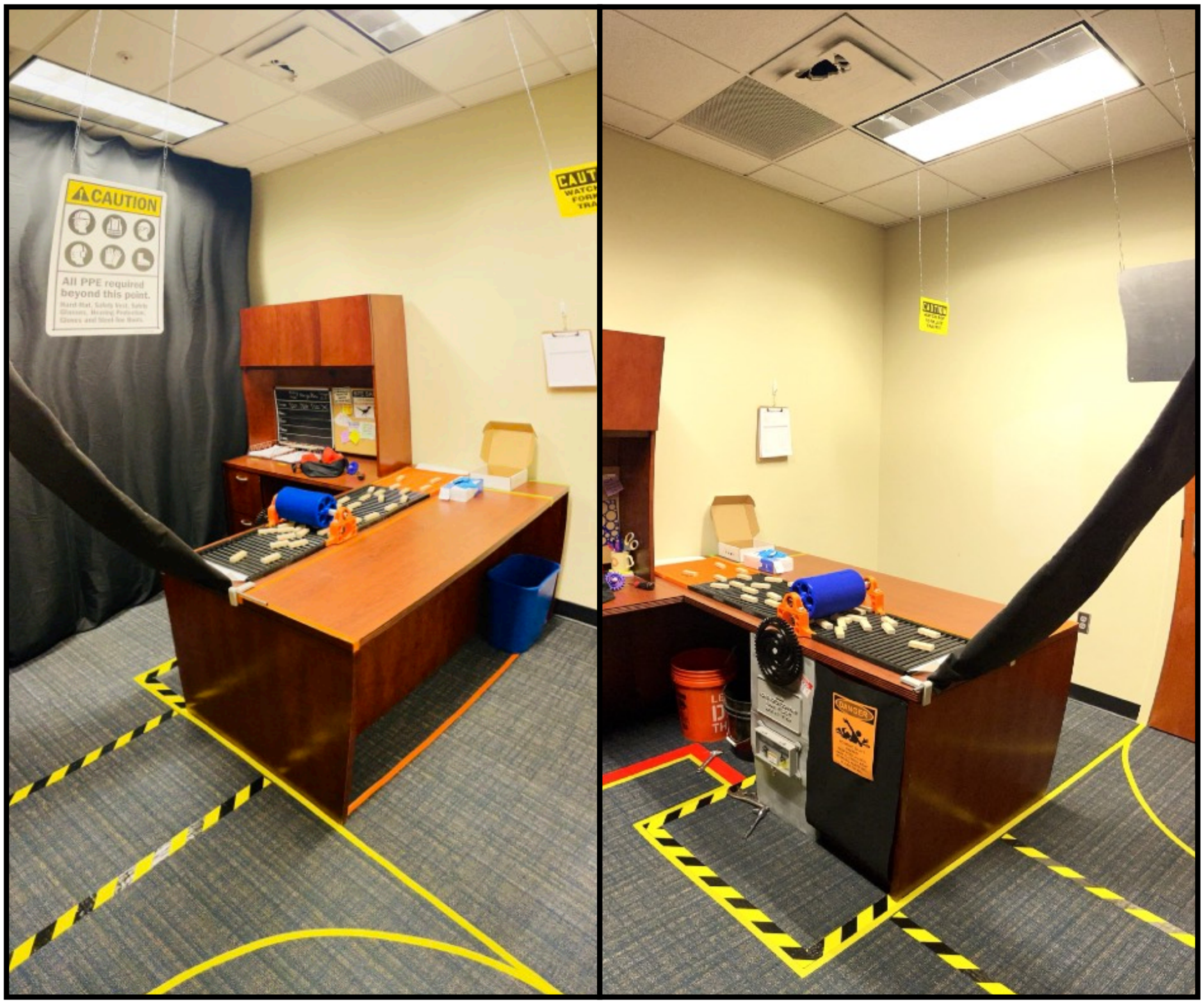

Figure 2: Two views of a sample scene.

and dial readouts for power and speed. Colored safety lines are denoted in tape around the area and throughout the scene in addition to some signage for safe practices.
A large black video conference call sheet is hung to denote the edges of the scene boundary. This sheet is also somewhat translucent from the other side, which is a useful opportunity for a teaching assistant to observe/manage the students without interrupting their investigation. The students are, naturally, informed of the person behind the curtain so they can ask questions if they are ever unsure whether a particular feature is an intentional clue or simply an artifact of the building process.

Students are encouraged to look for and photograph clues that indicate how/why the equipment failed, culpability, and to identify site safety concerns. The solution ultimately requires a comparison between the preliminary analysis results in the first stage and the physical evidence. An example is shown in Figure 3, where, one semester, the students had to identify a corrosion fatigue failure of the shaft at the shoulder bearing. The predicted location of failure along the shaft disagreed with the preliminary analysis. Approximately thirty to forty percent of the

Figure 3: Sample shaft failure scene and clues.

investigation teams noticed the discolored ceiling tile, which was located directly above the location of failure. The ceiling tile scrap was obtained from maintenance, and the discoloration was achieved with chalk that had a partially neon hue. The teams that noticed the tile had no confusion that it was a clue, though future iterations saw a more sophisticated reproduction of a deteriorated ceiling vent (Figure 2). The fracture surface also clearly supported the ceiling tile's presence as there was an intentional patina upon the fracture surface where a substance might drip from the ceiling to hasten the fatigue failure. Note that the patina is only present in the free surface or crack growth regions, and a representative fracture surface pattern was hand carved onto both faces of the failed shaft. This fracture surface is idealized so students can compare it to classic schematics for clear identification of a rotating bending fatigue failure exacerbated by a corrosive liquid.

Opportunities for customization: To deepen the lesson, a more complex piece of equipment could be brought in. Increased number of parts in the assembly will require a deeper analysis of more machine design topics. To iterate each semester, there are many opportunities to change the failure point and/or culpable party to avoid repetition. Once an instructor has four to five different failure scenarios, there is enough to avoid repetition for two years, limiting the opportunities for unwanted cross-feed between semesters and classes. For the example activity presented, there exist five different versions of the shaft, each having failed in a different place, through a different mode, with a represented fracture surface. To broaden the activity and scale it back, simply bring the failed assembly into the classroom for analysis without the investigation room. Even simplified for expediency, this is a worthwhile activity that will still require students to think critically to identify the failure mode and comment upon whether it was as predicted.

Phase 2, in the form presented in this publication, supports ABET Student Learning Outcomes 1 (identify, formulate, and solve complex engineering problems), 4 (ability to recognize ethical and professional responsibilities), 5 (function effectively on a team), 6 (analyze and interpret data, and use engineering judgment to draw conclusions), and 7 (acquire and apply new knowledge) [11].

Phase 3: Presentation. Teams are asked to develop a short powerpoint presentation that describes the identified clues, engineering analysis applied, and the resulting logic-supported conclusions. On the day of the presentation, a competition elimination bracket is set up to facilitate an informal debate.

Teams present two by two, and after each pair has made their case, the classroom is polled on which theory was more convincing. The winning theory progresses to the next round. After all the teams have presented at least once, the winning teams are asked to concisely sum up their case in one sentence, and they are then allowed to briefly debate each other on the merit of their investigation and conclusions. The room is again polled to choose the most convincing argument. This process is repeated until one victor emerges. After this, the instructor typically presents the true conclusion, which is always an entertaining time—especially if a team was correct but was not voted up to the next level.

Students are asked to reflect on the experience together in a classroom-wide discussion. The main takeaways typically regard:

- The criticality of due process, the formality of investigations, and the correct handling/interpretation of evidence.
- The power of perception, and how remaining impartial is paramount when the stakes are so high.
- The nuance and broadness of engineering as a profession and skillset. Equipment can be very sensitive to small elements, and a broad knowledge base is needed to not only understand the evidence, but to even know to look for it in the first place.
- Learning will be a continuous process throughout their career.
- Safety procedure, best practices, maintenance schedules, and Standard Operating Procedures (SOPs) in the workplace are consequential and not to be skimmed, dismissed, or delayed.

Opportunities for customization: To deepen the lesson, the teams may be prompted to write a report detailing their investigation, logic, and conclusion. Additionally, a set of recommendations to avoid future failures and improve the workplace would be an effective exercise to shift student thinking from the reactionary point of view towards the preemptive and preventive philosophy of safety management. To broaden the experience for expediency, the debate aspect could be removed. Students could then simply present their theories and discuss the learning experience with their classmates.

Phase 3, in the form presented in this publication, supports ABET Student Learning Outcomes 3 (communicate effectively), 4 (ability to recognize ethical and professional responsibilities), 5 (function effectively on a team) [11].

2.2 Lesson materials & advice for implementation

The same assembly in Figure 1 is utilized across semesters; however, the clues and failure location/mode can be adjusted for new solutions. This allows for the preliminary analysis of Phase 1 to remain consistent, but for the critical thinking aspect of the subsequent Investigation and Presentation Phases to remain new and fresh.

Phase 1 should be consistent when the instructor makes the analysis a teaching workshop, as it ensures the key learning objectives are always met semester to semester. However, Phase 2 should be somewhat flexible so that previous students cannot simply pass the solution on to the incoming students. When possible, maintaining an evolving storyline is desirable, as students who pass the class seem to take an interest in the next "chapter," so to speak. In the example discussed in this paper, whenever the culpable character "escapes responsibility," they remain in the "story" the next semester. Only when the culpable character is discovered does the story shift with new factory personnel and new, corrective procedures added to the scene. In this sense, the room is a living, ever evolving thing, that only requires updates when necessary—keeping the required time and effort on the instructor's part to a reasonable level. Utilizing the opportunities for customization presented in the previous section will assist instructors in slowly growing their activity to a large scale experience, rather than requiring a massive endeavor to erect the room all in one semester.

2.2.1 Buffing assembly design and sample clues

The buffing assembly is the heart of the activity, so this is the critical set of engineering clues that takes precedent in the hierarchy. Figure 4 shows a generalized schematic of the shaft design layout, which positions and secures the components (bearings, buffing wheel, and gear) along its length. Typically, for each "version" of the activity (each set solution that requires a different failure mode/location), two to four copies/duplicates of the shaft are required. One shaft is needed in the whole condition for Phase 1, and a duplicate shaft in the failed condition is needed

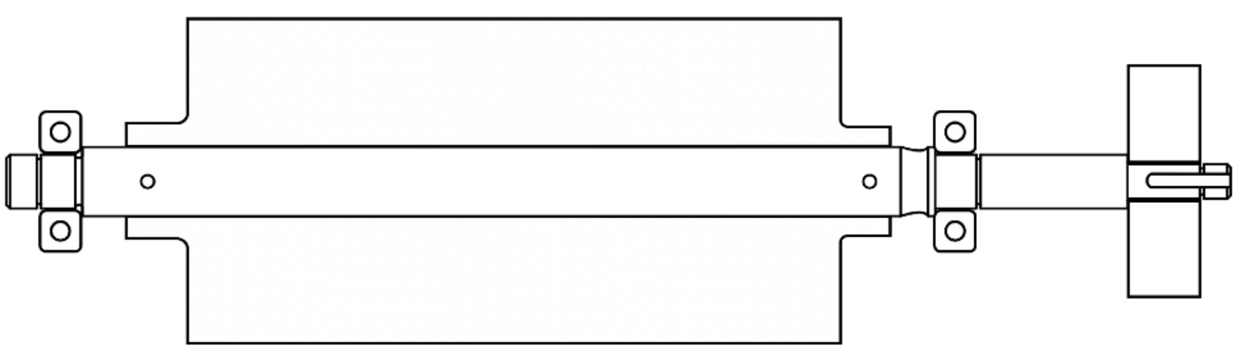

Figure 4: Buffing assembly general shaft layout.

for Phase 2. If the class enrollment is large, further duplicates of the shaft may be desired for improved time management during Phase 1.

The shaft itself was machined from an inexpensive metal with a silver coloring, which allows for greater customization options in naming different metals on the activity prompt to switch up material properties between semesters. The ball bearings were purchased. The gear, buffing wheel, pillow blocks, spring pins, and retaining rings were 3D printed out of PLA filament for customized fits and assembly convenience. This is especially helpful with the retaining rings, as real retaining rings require a special tool for installation. The buffing wheel was covered in a layer of felt to represent the buffing pad, which is a consumable and has a replacement schedule alluded to in the factory setting (log book planted in the scene).

The equipment is presented to the students during Phase 1 in the assembled state, and they are not permitted to disassemble it. Typically, duplicate shafts without any components are made available for ease of measurement and to accommodate larger class enrollments. Students are able to physically access and measure the shaft, gear, and buffing wheel, but cannot access the 6204-C3 ball bearings in the pillow blocks well enough to obtain that information directly. Rather, the students must look up the bearing sizing and shape in a catalog.

During their preliminary step shaft analysis, the students must account for several different types of features, including retaining ring grooves, shoulder fillets, through holes, a keyway, and a stress relief groove. This reinforces the stress concentration factor lesson in several different forms. Additionally, the loading of the components upon the shaft must be accounted for in different ways. For example, the bearing and gear will be approached in a typical manner, but the buffing wheel must account for the sleeve over the through holes. The torsional loading is driven by the contact surface upon the product, but that loading is transferred to the shaft via a longer geometry. Obtaining an appropriate free body diagram is a review challenge in and of itself.

Once the activity has progressed to Stage 2, the buffing wheel assembly must be staged in the failed condition. This will mean cutting the shaft at the point of failure and mimicking the fracture surface that corresponds with the chosen failure mode. In the example presented, the fracture surface was achieved by carving the general topography using a rotary flex shaft, and adding the representative striations using a v-shaped graver. Figure 5 demonstrates two different examples of fracture surfaces manufactured in this way. If the selected method of construction is to carve the fracture surface, as it was in this example, it is a good idea to machine the shaft itself out of a soft aluminum or low carbon steel for ease of cutting (machinability). However, this is not necessarily within the skillset of all instructors. Other options would be to glue a paper fracture surface schematic to the ends the shaft, or to model the shaft and 3D print the appropriate topography. Another option is to provide a professional image of a representative fracture surface as part of the soft material, which would be especially appropriate if the activity has been customized for a small scale implementation.

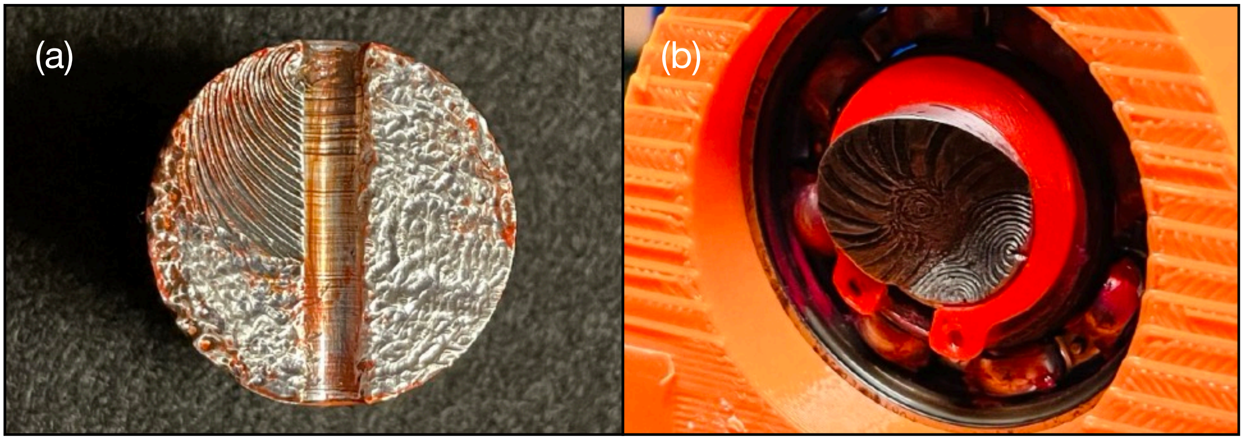

Figure 5: Sample fracture surfaces that mimic textbook schematics for (a) rotating bending fatigue with corrosion, and (b) torsional fatigue failure.

2.2.2 Motor design and clues

The next area is the variable motor station (Figure 6), which "drives" the large gear and indicates the speed and power settings. Due to the size and stability requirements of the motor, it was constructed out of a large cardboard box that was spray painted silver. The large gear was 3D printed out of Hatchbox PLA filament and was mounted on a wooden dowel posted through the motor chassis. While the cardboard is a low fidelity replica of a metal motor chassis, three aspects allow for the suspension of disbelief:

- The gear turns, which is a tactile detail the students thoroughly enjoy.
- The speed and power indicator has a high resolution of detail, which draws focus away from the plain cardboard chassis.
- There is sufficient signage to engage student attention.

Figure 6: Motor station, and a close-up view of the speed and power indicator.

Often, the cardboard chassis and wooden dowel go entirely unnoticed unless specifically pointed out. This is one of the keys to creating a successful, low-budget escape room—knowing what to include, what to leave out, and where to draw focus.

The proper settings are indicated in the activity prompt (example in Figure 1), and the actual settings on the motor are an excellent opportunity to plant a clue. For example, one semester, the power and speed settings were counter to the official recommendation. Approximately half of the teams noticed, and it was a critical clue to the reason the shaft failed—surpassing the critical speed. Determining the failure mode and the physical cause is not the end of the game, however, as the culpable party must still be identified. This is when the human element comes into play, often requiring further investigation of the employee workstation.

2.2.3 Employee desk area design and sample clues

The employee workstation in the staged scene includes several clues eluding to the state of the work environment, employee mindsets, and even some business matters. Figure 7 shows one version of the employee workstation, which includes a number of notable story elements. The blackboard contains a list of working personnel and a quick-glance checklist that shows what has been inspected that week and when the inspection occurred. There are a number of messages that range from humorous easter eggs (the velociraptor sign never fails to amuse) to employee details. For instance, there is a note congratulating Nancy on a recent promotion, and another inquiring about a delayed order for bearing grease. In one iteration, the promotion note

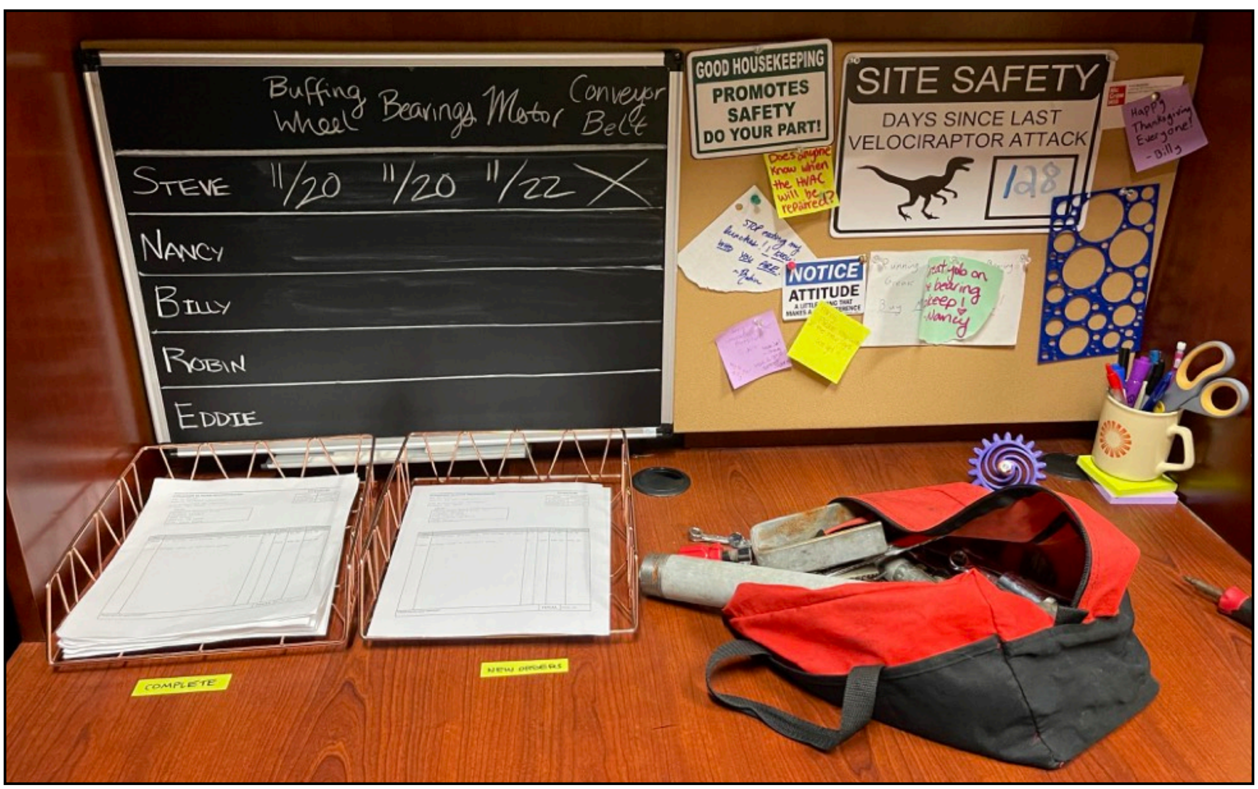

Figure 7: Employee workstation from the staged factory scene.

coincided with a tear-stained rejection letter in the garbage bin that pointed to a disgruntled employee neglecting their tasks.

Also on the desk is an inbox and completed box for invoices. These invoices have date and time stamps, fake account numbers and billing addresses, and product volumes. One semester, this was a critical clue to solving the equipment failure where the invoices had piled up and an employee had adjusted the motor speed and power to increase production. However, the employee had not taken into account the critical shaft speed, and exceeded the limit and caused the equipment to fail. The invoices are also a fun way to add entertaining easter eggs, such as incongruous order volume with respect to the billed amounts that suggest the company has an embezzlement scheme afoot!

Also found in this section of the room are the employee logbooks, a sample of which can be viewed in Figure 8. They are "hidden" in the drawers, alongside the bearing grease, spare shaft, and other random tools. The logbook provides dates, actions taken, task owners, and shutdown/start-up details. Each employee has a unique handwriting style and a favored pen color. Students are expected to review the logbook and gain insight on the standard maintenance practices that will then inform them of the circumstances under which the equipment failed.

These logbooks have been continuously updated each semester and maintain the artifacts of the previous solutions from semesters past. As the company employees experience one kind of failure, they learn from it, potentially fire someone if they are caught as the responsible party, and implement new SOPs. This level of detail is not necessary, but it has been an enjoyable

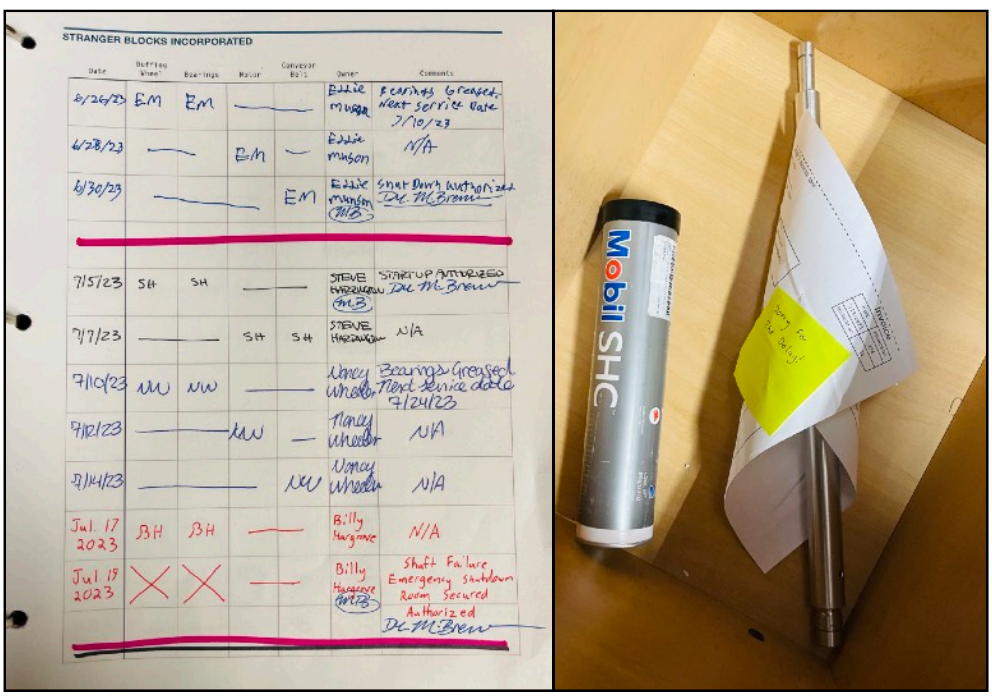

Figure 8: A representative page of the logbook, and the contents of a drawer.

challenge to maintain the storyline continuity and has become something of a private joke. This is not to be underestimated, as it has excited and motivated teaching assistants and past students to add their own story installation to the ongoing activity!

2.2.4 Cardinal design recommendations

The most important design lessons learned when constructing and running the forensic investigation activity are as follows:

1. *An achievable solution*. When choosing the embedded lesson (ex: importance of bearing lubrication, beware corrosion, etc), remember to keep it achievable. For example, make a resource page available to the students that includes all the information they need to fully solve the mystery. This keeps the outcome achievable, and encourages exploratory learning—an important career skill.
2. *Do not overbuild.* Utilize a small space to achieve a high resolution of detail. A large room is difficult to fill with clues, and students will require more time to search the larger area, even with the same amount of clues.
3. *Life is three-dimensional.* This can be easily achieved with hanging signs. In this example, there was a chute "from nowhere" that is considered a "wow factor" for the students. It is not detailed or particularly believable—in fact, it is one of the least quality parts in the room—but the verticality lends an impression that the room is larger than it is, and provides a more dynamic exploration experience.
4. *Hide easter eggs.* Identify a popular show or book currently sweeping the student population and hide little references in the room. In this example, all the employees are named after characters in a popular television show, in this case "Stranger Things". The company name is "Stranger Blocks, Inc". Addresses listed on invoices are from the show script or filming locations. This amuses the students and excites them when discussing "who dun it".
5. *Honor Agatha Christie.* When planting clues, lay relevant red herrings/distractions for the students to follow, but do not pull things from thin air when developing the true solution. Provide enough variation to lead the teams to different conclusions to keep the presentations engaging, but not so much variation that they feel tricked when you explain "who dun it".

2.2.5 Useful construction supplies

On a final note regarding construction tips, the following products were utilized to achieve a robust and detailed affect on a low budget:

- Amazon Basic metal rods marketed for erecting cube storage spaces are inexpensive, numerous, and very useful for several things. They allowed for a cost effective construction of the conveyor system, and they formed the base structure for the felt-covered chute leading from the ceiling.
- Painters tape in various colors and patterns was utilized to form the basic safety lines for personnel moving about the room. This is an inexpensive and easy set of details that can add a dynamic element to the room and important discussion points to the students' investigations.

- Jenga blocks were used to represent the products undergoing buffing. They are inexpensive, simply shaped, robust, and uniform.
- Sticky-backed velcro was an essential tool in securing the room components together. This allowed construction on the standard issued furniture without permanent damage. It also allows for a flexibility in structure that is is easy to repair between investigation teams in the event anything becomes accidentally dislodged.
- 3D printing with Hatchbox PLA filament was heavily utilized to make custom parts to fit in the small office space. Examples include, but are not limited to, the conveyor system roller supports, the joints of the chute, the pillow blocks housing the buffer shaft bearings, the gears powering the buffer shaft, the buffing wheel component, and the motor box with speed and power dials.

3. Assessment results

Assessment of the learning is predominantly from the verbal discussions during Phase 1 as compared to Phase 3, and the blind class reviews at the end of the semester. Assessment is ongoing as the forensic engineering activity is iterated and evolved semester to semester. All observations and feedback indicate that the forensic investigation activity is beneficial to both academic accomplishment and student perception. Finally, the activity has recently proven to be a strong talking point for job interviews.

Verbal discussion with students demonstrate the shift in both understanding and perspective. Prior to the investigation, during Phase 1, student discussions are more grounded in analytical process with excessive simplifications/idealizations. Once they move forward with the investigation of the failed part, the students seem to circle back and take a more realistic approach to the shaft analysis. There is a bias towards looking outward for assistance/solutions, such as asking the professor, rather than asking their teammates or doing research into the matter at hand. If an answer is not readily available, there seems to be a stall in progress. Students tend to maintain a reactionary mindset.

Discussions after Phase 3 tend to be grounded less in the textbook lessons and more in the reality of components in service. This is typically where they begin to compare small yet crucial details, such as comparing the bearing edge radius with the shaft shoulder fillet radius. While students discuss their theories with other teams, they tend to be more self-driven and eager to research information on the spot to better debate their points. One notable example one semester, after all the presentations had been completed, was an excited discussion that arose regarding the ambient temperature effects upon bearing grease. Without prompting, students pulled out their phones to begin searching for supporting articles on their theories regarding bearing grease procedures. Students seem to shift into a creative and proactive mindset with a bias towards seeking knowledge and initiating collaborations towards a solution. Additionally, students have an excited, positive and animated demeanor at this point of the activity, and often state that they “finally understand how all the different lessons tie together.”

Blind reviews are conducted at the end of the semester, and students frequently express favor for the forensics investigation activity. Selected student quotes from anonymous end-of-semester course surveys:

- "Was very creative in the assignments which were more engaging and required critical thinking." (Fall 2022)
- "The last couple of weeks (shaft design and adventure activities) were helpful and fun." (Fall 2022)
- "I think that Dr. Sterling did a good job creating real world problems and getting our feet wet with real world tools." (Fall 2023)
- "I loved the activities and the mystery game we did." (Summer 2023)
- "I thought it was really cool that you talked about the failure analysis job, and I had already considered a similar path from working my co-op. " (Summer 2023)
- "This class completely reshaped my view of materials and machine design….The activities were a great way to apply theoretical knowledge to the real world which is definitely something most classes in the curriculum tend to lack." (Summer 2023)
- "The activities in this class are helpful and allow us to use the skills in real life examples." (Spring 2023)
- "I loved Dr. Sterling's teaching style because everything we learned was tied to industry and real-life situations which is typically overlooked." (Spring 2023)

The blind reviews demonstrate that the students appreciate the creative approach to the forensic investigation activity because it emphasized real-world problems and tools. Students valued the practical application of the theoretical knowledge they had gained over the semester, and enjoyed seeing how it can connect to industry situations. Not only did they expand their knowledge base, but a number of students reexamined their career paths within the context of their new experience. Overall, the forensic activity appears to bring the engineering material alive for many students.

Finally, some students have recently reported that the forensic investigation activity has become a point of discussion during their job interviews to positive effect. A student was willing to share their experience in detail:

> "*I thoroughly enjoyed your Machine Design class this spring and am extremely grateful for the incredible experience of doing the forensic analysis activity. That has been very beneficial in various interviews.*
>
> *The forensic activity was very interesting as well as beneficial to my future career. It provided me with experience that covered the entire range of a real-world engineering problem from start to finish. The first portion of the project - taking measurements of and analyzing a metal shaft - provided an opportunity to take what we had learned in the class on the theoretical level and apply it to a real life scenario. It taught us what kind of measurements are necessary to fully define a problem as well as what kind of techniques are*

best suited for taking those measurements. This helped us to visualize what is actually going on when we are provided with diagrams and dimensions in a textbook-style problem. Additionally, it gave us an opportunity to apply many of the techniques we learned in individual assignments such as fatigue analysis, stress concentrations, and more in a single, all encompassing, problem.

The second portion of the project - the analysis of the scene of failure - provided an extremely unique opportunity to apply engineering analysis skills to not only a mechanical problem, but also a forensic problem. In addition to examining the broken shaft to determine if it matched predicted failure methods, we also needed to examine the surroundings as well as employee documents to determine possible human error or negligence. This required searching and analyzing the scene for evidence of protocols that had not been followed or external factors that could have caused premature failure. This aspect in particular, has been very beneficial to me as I have interviewed with companies. I am pursuing a career in the defense or intelligence industries, and having this experience has been invaluable. I am able to demonstrate to potential employers that I am capable of using analytical skills developed through my engineering curriculum and applying them to forensic-style investigations. Companies have always been extremely interested in this project on my résumé, and it is definitely a high talking point. I'm extremely grateful to have gained this experience through Dr. Sterling's class."

Overall, the activity has been very well received with many educational benefits to the students. Bottom line, the students are positively and effectively engaged with the material in a long-lasting way, and the semester ends on a very high note.

4. Summary conclusions

The Forensic Investigation Activity presented in this paper supports engineering education by providing an immersive learning experience that integrates theoretical knowledge, practical skills, teamwork, ethical considerations, and continuous learning – all essential skills a student needs for a successful career in engineering. The activity follows a three-stage structure: Preliminary Analysis, Investigation, and Presentation. Each stage offers students hands-on experience in various aspects of engineering, including data collection/analysis, critical thinking, and technical presentations.

1. The Preliminary Analysis phase involves receiving a scenario prompt, performing an initial analysis of an equipment assembly, and confirming the reported design adheres to typical practices. This phase of the activity supports ABET Student Learning Outcomes 1 (identify, formulate, and solve complex engineering problems), 5 (function effectively on a team), and 7 (acquire and apply new knowledge).
2. The Investigation phase allows students to explore a staged equipment failure scene, identify clues, and build theories. This phase of the activity supports ABET Student Learning Outcomes 1 (identify, formulate, and solve complex engineering problems), 4 (ability to

recognize ethical and professional responsibilities), 5 (function effectively on a team), 6 (analyze and interpret data, and use engineering judgment to draw conclusions), and 7 (acquire and apply new knowledge).

3. The Presentation phase requires evidence-based solutions presented in a clear and cohesive manner. This phase of the activity supports ABET Student Learning Outcomes 3 (communicate effectively), 4 (ability to recognize ethical and professional responsibilities), and 5 (function effectively on a team).

This structure aims to develop students' skills in identifying, formulating, and solving complex engineering problems, working effectively in teams, and acquiring new knowledge. The activity is designed to be customizable, allowing instructors to adapt the depth, breadth, complexity, and duration of each stage based on their preferences and class requirements. The three phases align with ABET Student Learning Outcomes, emphasizing problem-solving, teamwork, communication, ethical responsibilities, data analysis, and continuous learning.

Post activity assessment (verbal evaluation and anonymous class reviews) demonstrates positive feedback from students, indicating increased understanding, a shift in perspective, and a strong appreciation for the real-world application of engineering principles. A number of students also express appreciation for the early exposure to an interesting, yet oft-overlooked engineering career path.

This paper provided practical advice for implementing the activity, construction tips, and useful materials for staging an impactful yet low-budget forensic investigation room scene. A brief summary of the key advice is as follows:

- **Consistency in Preliminary Analysis Phase:** Select an assembly that can fail in multiple ways, depending on the scenario. This allows instructors to maintain consistency in this phase across different semester to ensure the learning objectives are consistently met.
- **Flexibility in the Investigation Phase:** Change the location and mode of failure of the assembly across different semesters to prevent the easy transfer of solutions between students who have already completed the class and incoming students. An evolving storyline with recurring characters enhances engagement.
- **Use of Low-budget Materials:** Prioritize achieving high resolution of detail in a small space over extensive construction. Use low-budget materials for constructing the investigation scene, such as Amazon Basic metal rods, painters tape, sticky-backed velcro, and 3D printing with Hatchbox PLA filament.
- **Three-Dimensional Design:** Leverage three-dimensional scene elements to create a dynamic exploration experience. Hanging signs and incorporating clues on the ground and upon the ceiling can give the impression of a larger space and add a "wow factor."
- **Incorporate Easter Eggs:** Integrate popular culture references or "easter eggs" into the activity, making it more engaging and enjoyable for students. This can enhance their interest and excitement during the investigation and help kickstart discussions.
- **Balance Achievability and Challenge:** When choosing the embedded lesson the investigation centers around, ensure that the solution remains achievable for students.

Provide a resource page with necessary information, encouraging exploratory learning while keeping the outcome realistic.

- **Red Herrings and Clue Placement:** Lay relevant red herrings or plausible distractions for students to follow during the investigation, but do not pull things from thin air when developing the true solution. Provide enough variation to lead the teams to different conclusions to keep the presentations engaging, but not so much variation that they feel tricked when the true solution is revealed.
- **Continuous Evolution:** Consider allowing the forensic investigation activity to evolve and iterate semester to semester. Introduce updates when necessary, such as changing characters or procedures in response to student findings, to maintain storyline continuity without requiring massive reconstruction efforts. This allows for instructors to maintain the same general room scene, which reduces the amount of new construction required across different semesters.
- **Real-world Relevance for Job Interviews:** Recognize that the activity has proven to be a strong talking point in job interviews, so choose industry-relevant failure modes (such as improperly greased bearings). Students appreciate the real-world problem-solving skills gained, and employers express interest in the unique experience provided by the forensic investigation activity.

In summary, the Forensic Investigation Activity has proven to be a successful and engaging educational tool, fostering critical thinking, problem-solving, and practical application of engineering knowledge. The positive student feedback and its mention in job interviews underscore its effectiveness in preparing students for real-world challenges in the field of engineering.

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