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Troubleshooting Lab for Circuit Courses in the Electrical and Computer Engineering Program

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Abstract: Troubleshooting skills are an important and integral part of good engineering practice. This skill represents the ability to identify and fix a problem within an engineered system in a time-constrained setting. However, such important engineering skills do not come to students naturally, and it has been a long-standing concern within the Electrical and Computer Engineering programs that most of the students did not gain strong troubleshooting skills by the time they graduated. To address this issue, several faculty members in the Electrical and Computer Engineering programs have developed an initiative aimed at helping students develop and/or improve troubleshooting skills and, more importantly, build a solid foundation for successful professional careers in the future.

In the initial phase of this project, a troubleshooting laboratory activity was designed and implemented in Fall 2023 and Spring 2024 for Network Theory I, an introductory circuit course required for both Electrical and Computer Engineering students. During the troubleshooting activity, students worked in teams to identify and correct intentionally introduced errors in a constructed circuit. After identifying the errors, they were asked to correct them and then to demonstrate a fully functioning circuit through testing.

After the troubleshooting activity, students completed an anonymous questionnaire featuring multiple-choice and open-ended questions. The survey's objectives were to evaluate the lab's effectiveness, gather insights on how to improve it, and explore the possibility of extending similar troubleshooting activities to other courses. Although the students' feedback collected from the two semesters has been positive and encouraging, indicating an initial success of the troubleshooting activity, additional iterations are needed to collect more data to achieve the survey's objectives as well as to inform the development of an assessment strategy.

Introduction

Industry 5.0 emphasizes a human-centric design approach, in which humans and cobots (collaborative robots) collaborate in shared working environments [1],[2]. Cobots will handle repetitive and labor-intensive tasks, while humans will focus on customization and critical thinking activities to solve complex issues [3]. Industry 5.0 has gained increasing attention in recent years because it is considered the next major global industrial revolution. As part of the industry 5.0 implementation, the demand for a skilled workforce capable of solving problems creatively and adapting to changing situations has been on a steady rise. As a consequence, current employer demands place more emphasis on the value of soft skills, such as critical thinking, problem-solving, communication, collaboration, and creativity, which amount to 40% of all skills required by employers [1] and are considered essential to navigating the technological advancements as well as adapting and managing complex situations that will arise in a highly automated workplace [3].

Critical and problem-solving skills are needed to identify, troubleshoot, and resolve issues related to technology implementation. Troubleshooting is a fundamental part of the problem-solving skill that consists of (1) determining why something does not work as expected and (2) explaining how to resolve the problem [4], [5]. Despite being regarded as a critical and integral part of good engineering practice by industry, troubleshooting is often neglected in numerous professional contexts [6]. To ensure that the future workforce is equipped with the necessary hard and soft skills to thrive in this evolving scenario posed by Industry 5.0, educational institutions have the responsibility to prepare students to be career-ready and to tackle the future labor market challenges [7],[1].

Several studies have investigated different methods to improve students' troubleshooting skills since teaching and/or learning of troubleshooting skill has not yet been given much attention [7],[8]. Authors in [9] conducted an experiment to study whether collaborative learning can improve students' troubleshooting skills compared to individual learning in the field of robotics. Students were asked to construct, build, and program a robot both individually and collaboratively as a group. The study findings showed that collaborative learning does not outperform individual learning in improving students' troubleshooting skills. In a work in progress [10], several engineering faculty members at Kennesaw State University proposed a long-term intervention plan to add instructional materials and/or assignments to a wide range of engineering courses to help engineering students develop troubleshooting skills. However, their plans were interrupted due to the Covid-19 pandemic, and the preliminary study had been limited to evaluating students' skill level pre-intervention. In [11] a technology enhanced learning environment (TELE), called PHyTeR, was created to develop troubleshooting skills among computer science undergraduates. PHyTeR is a platform that guides students through multiple learning activities with scaffolding and feedback to practice a structured approach of troubleshooting. The pilot study reported that students who had interacted with the learning environment started to grasp some key elements in identifying and resolving computer networking issues, but only one troubleshooting scenario had been tested with many instructional scaffoldings still in place. Authors in [12] designed circuit troubleshooting exercises that were embedded in fundamental DC electric circuits labs for first-year engineering technology students. Three troubleshooting sessions with increasing complexity were embedded in a series of conventional lab exercises to challenge students to identify and solve one or more unknown faults in the circuit. Out of the 66 students who participated in the sessions, only 42 students completed all three exercises and 30 students who took the survey were included in the assessment conducted through instructors' evaluation and student feedback. Almost half of the students who completed all three sessions showed improvement from the first to the last assigned and 86% of the surveyed students agreed or strongly agreed that the lab exercises helped them improve their troubleshooting skills. In [13] 20 instructors of electronics courses from 18 different institutions were interviewed about their practices related to troubleshooting instruction in electronics lab courses. Survey results show that almost all instructors identified that developing students' ability to troubleshoot was a central learning goal for electronics courses, however, only half of them assessed students' troubleshooting ability. This suggests that there is a need to develop research-based, process-oriented assessments on students' ability to troubleshoot electric circuits.

Therefore, this paper presents the design, implementation, and assessment of a troubleshooting laboratory activity for a DC circuit course (Network Theory I) that is a required course for sophomore Electrical engineering (EE) and Computer Engineering (CE) students at Wentworth Institute of Technology (WIT), located in Boston (MA)..

Troubleshooting Laboratory

The main objective of the troubleshooting laboratory is to provide students at the entry level with the opportunity to practice identifying, isolating, and solving problems in a physical system. Since the laboratory was developed for an introductory electric circuit course, the emphasis of the troubleshooting experience was placed on construction and testing of a DC circuit.

The development of the exercise started with identifying the common mistakes that students tend to make. These common mistakes, which have been classified into three categories as provided in Table 1, were drawn from instructors' many years of first-band experience in supervising student laboratory exercises. By introducing a combination of some of the identified mistakes in Table 1, five different problematic versions of the circuit as shown in Figure 1 were created. In every problematic version, five mistakes from Table 1, with at least one from every category, were randomly selected and implemented. For instance, the five mistakes in one problematic version of the circuit are (1) the 6 V voltage source is shorted on the breadboard by placing the positive and negative jumper wires in adjacent connected sockets, (2) the polarity of the 12 V voltage source is reversed, (3) resistor R_9 and R_7 are swapped, (4) resistor R_1 and R_6 are shorted on the breadboard by placing their two terminals in connected sockets, and (5) the negative terminal of the 6 V voltage source is not connected to resistor R_3 or R_5 by placing the negative jumper wire of the voltage source in a socket that's not connected to the resistors.

Category of mistakes	**Description of the mistakes**
Power sources	Inappropriate operation on a DC power supply (*e.g.*, using GND in place of the negative terminal)
	Shorting the positive with the negative terminal (on DC power supply or on breadboard)
	Incorrect polarity
Components	Incorrect component values
Connections	Shorting out a component
	Failure in establishing electric connection

Table 2: *Common mistakes made by students when constructing and testing DC circuits.*

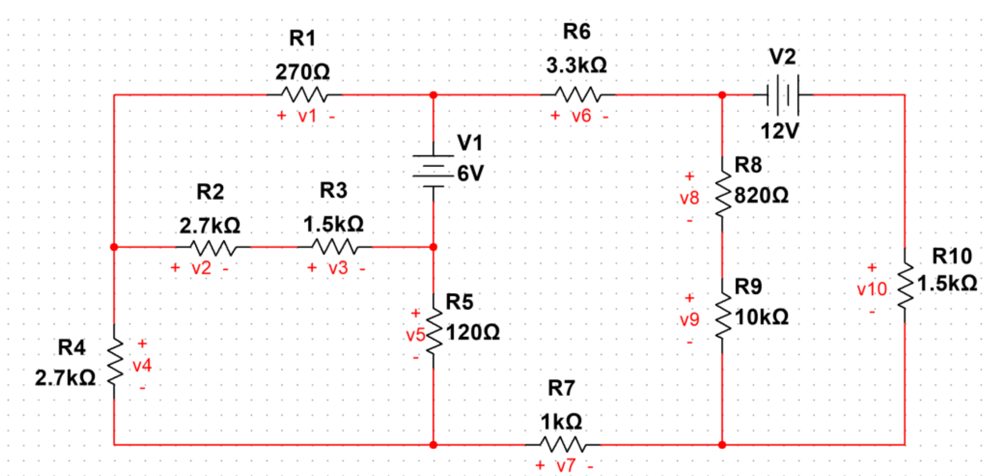

Figure 1: *Two-Source DC Circuit used in the troubleshooting circuit*

The deployed troubleshooting laboratory exercise contains the following student activities:

1. Simulate the voltages and currents of all resistors in the circuit as given in Figure 1. The simulation results establish the theoretical expectation, which serves as the reference to be compared with measurement.
2. Measure the resistors' voltages and currents on a provided physical circuit, which was constructed in advance and contains five mistakes.
3. Compare the measurement with the simulation results to determine if the provided circuit is properly constructed. If the measurement does not comply with the simulation, identify and document the problems in the circuit.
4. Resolve all identified problems in the circuit. Students were strongly discouraged from dissembling the circuit and reconstructing it from scratch. Instead, they were asked to only change the parts of the circuit where the issues were identified.
5. Repeat step #3 and #4 until the measurement matches the simulation.

Survey Data

At the conclusion of the laboratory activity, students were asked to individually complete an anonymous survey. The survey aimed to capture students' perceptions about the utility and difficulty level of the troubleshooting exercise and also to collect their opinions on extending the troubleshooting activities to other circuit courses. Additionally, two open-ended questions were included at the end of the survey to gather feedback on the most challenging aspects and the most beneficial parts of the laboratory exercises. The eight survey questions are provided in Table 2 along with their respective rating scales.

#	Questions	Answers
1	Rate the difficulty level of the troubleshooting tasks.	a) Easy b) Moderate c) Challenging d) Very challenging
2	How satisfied are you with your performance in the troubleshooting lab session?	a) Very Satisfied b) Satisfied c) Neutral d) Dissatisfied e) Very Dissatisfied
3	How well did the labs during the semester prepare you for the troubleshooting tasks?	a) Excellent b) Good c) Fair d) Poor
4	How useful was the troubleshooting lab in enhancing your understanding of circuit concepts?	a) Not Useful at all b) Slightly Useful c) Moderately Useful d) Very Useful e) Extremely Useful
5	How would you rate the overall effectiveness of the troubleshooting lab session?	a) Excellent b) Good c) Average d) Fair

		e) Poor
6	Based on your experience, would you recommend implementing similar troubleshooting labs in other related courses?	a) Definitely Recommend b) Somewhat Recommend c) Neutral d) Not sure e) Do Not Recommend
7	Which specific aspects of the lab exercise did you find most challenging?	-
8	Which specific aspects of the lab exercise did you find beneficial for your learning?	-

Table 2: *Survey questions and the respective rating scales.*

Results

100% of the 27 students, who were enrolled in two sections of the same course (one in Fall 2023 and the other in Spring 2024) taught by different instructors and participated in the laboratory exercise, completed the questionnaire. Survey results are illustrated using bar graphs for better visualization and are shown in Figure 2 – 7, which present the percentage of students versus the respective rating scale for question 1 to 6, respectively.

Figure 2 depicts the distribution of students' perceptions regarding the difficulty level of the lab activity. Notably, 70% of the students rated the troubleshooting exercise as moderate, while none perceived it as very challenging. This trend may be linked to the collaborative nature of the activity, where students worked in groups of two to three. Group collaboration likely enhanced peer support and facilitated collective problem-solving, however potentially lowering the perceived difficulty. Additionally, it is important to note that, when students took the survey, they had not yet been confirmed if they had successfully identified all the embedded mistakes or if they had appropriately resolved the issue(s), which could have influenced their perceptions. Nevertheless,

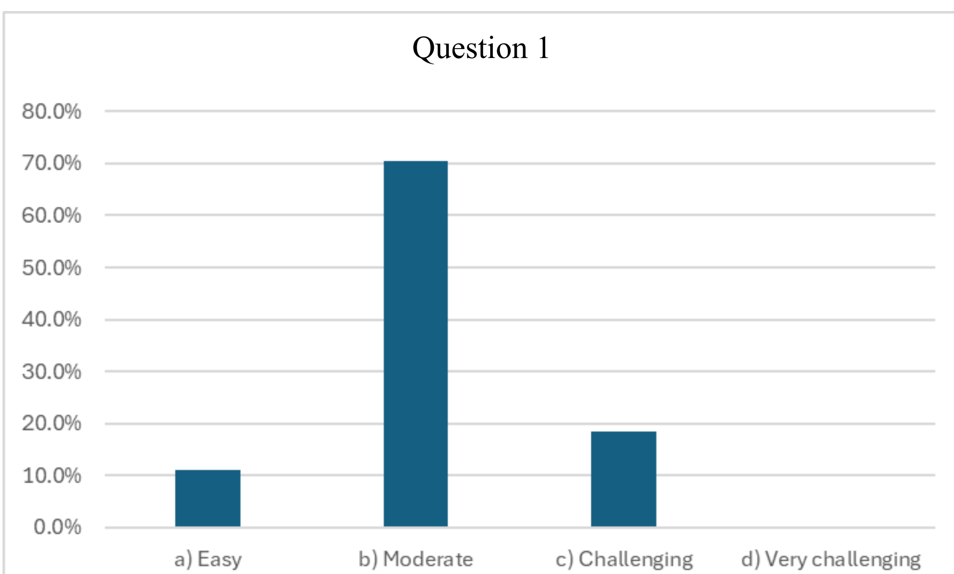

Figure 2: *Survey results for question 1*

the troubleshooting exercise could be made more challenging by converting it to an individual effort or using a more complex circuit.

Figure 3 illustrates students' satisfaction with their performance in the troubleshooting lab. Nearly 80% of the students reported being satisfied, while only 7% expressed dissatisfaction. According to a previous study that has demonstrated a positive linear correlation between academic performance and student satisfaction [14], the high satisfaction rate holds the promise of achieving the objective of the troubleshooting exercise, which is to develop and enhance problem-solving skills to foster student success.

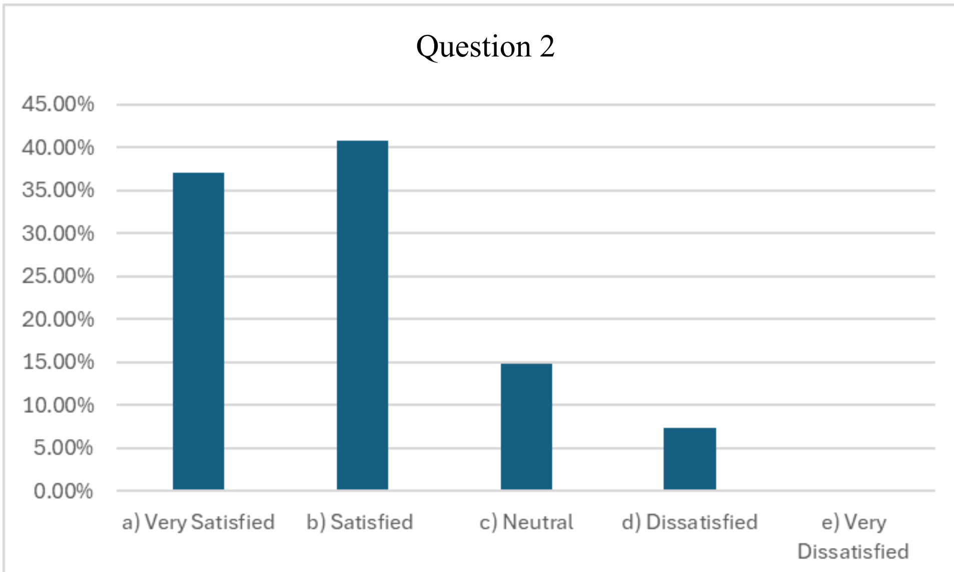

Figure 3: *Survey results for question 2*

Questions 3 and 4 aim to explore the connection between the troubleshooting lab activity and the broader course objectives. Specifically, Question 3 seeks to determine whether the preceding laboratory exercises have effectively prepared students for the troubleshooting tasks. The results collected for Question 3, as shown in Figure 4, provide valuable insights into this relationship. Although the earlier labs that took place before the troubleshooting exercise did not include tasks explicitly labeled as "troubleshooting," some activities were intentionally modified to incorporate open-ended questions, some of which were intentionally designed to have no clear-cut correct answers. These adjustments were intended to help students develop and strengthen critical thinking, independent reasoning, and problem-solving skills through a more exploratory learning experience. Figure 4 reveals that nearly 80% of students rated the previous lab activities as either "good" or "excellent" in helping them perform well in the troubleshooting task. This high percentage underscores the importance of incorporating open-ended exercises early into the curriculum on a more regular basis, which appears to be more effective at preparing students for real-world problem-solving scenarios.

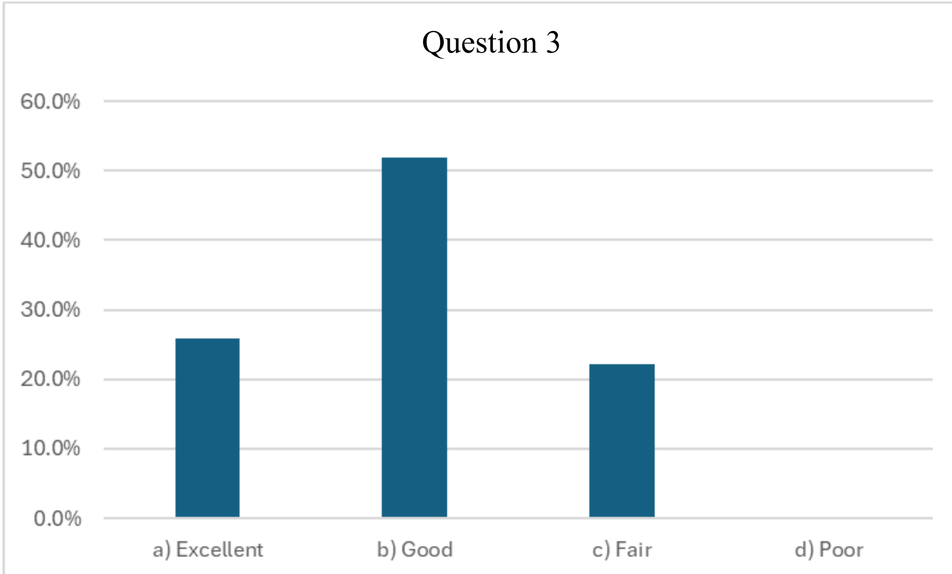

Figure 4: *Survey results for question 3*

Figure 5 presents the results for Question 4, where students were asked whether the troubleshooting lab was effective in enhancing their understanding of circuit concepts. As observed in previous students' practice in constructing and testing DC circuits on a breadboard, students tend to repeat the same mistakes, which is likely due to a lack of strong understanding of circuit theories. The troubleshooting lab, therefore, was designed to address this issue by forcing students to apply the basic circuit concepts to identifying and resolving problems without any assistance from instructors. The survey data highlights the activity's impact on the intended objective, with an overwhelmingly high percentage (89%) of students finding it either "very useful" (41%) or "extremely useful" (23%). It is worth noting that the activity was conducted in groups, and the difference in engagement levels among members may have likely resulted in various learning

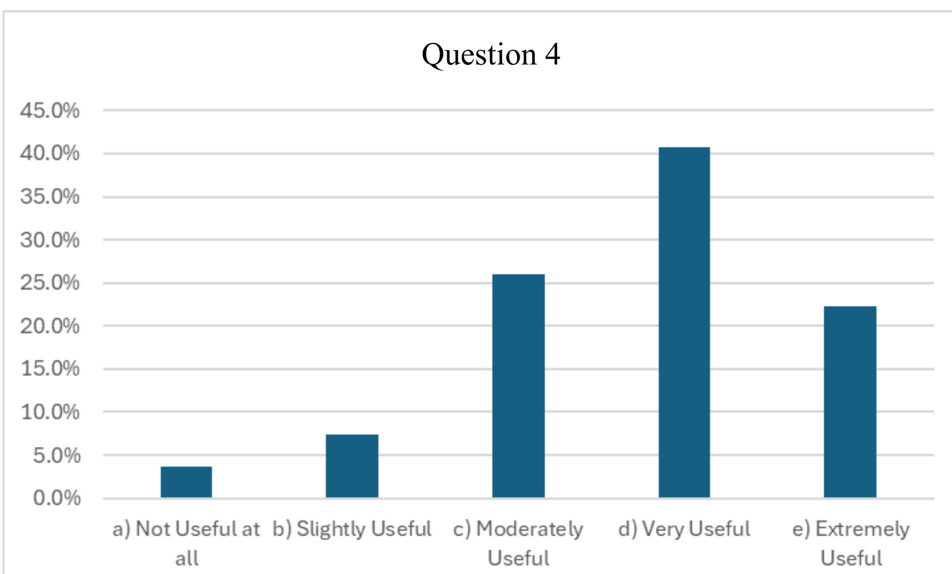

Figure 5: *Survey results for question 4*

outcomes, where more-engaged students regarding the exercise as more useful in enhancing their comprehension of circuit theory and practical application. Nonetheless, the result demonstrates the value of troubleshooting exercises in deepening students' grasp of circuit concepts through hands-on, reflective learning.

Figure 6 illustrates students' perceptions of the effectiveness of the lab activity in developing or enhancing their troubleshooting skills. Troubleshooting is often regarded by students as a particularly daunting and challenging aspect of engineering practice. This perception can lead to hesitation in or, in the worst scenario, avoidance of initiating and/or participating in a troubleshooting task, which results in a facetious cycle where the more lacking the students are in troubleshooting skills the less practicing opportunities they seek. The key motivation of developing the troubleshooting activity is to break the cycle by placing such important engineering practice at the center of the stage as the main and only outcome of a laboratory exercise. The survey data shows that 82% of the students rated the activity good and excellent overall for its effectiveness in their troubleshooting skills, and none of the students reported the exercise as ineffective. This positive perception of the activity's impact suggests that having students troubleshoot an engineering system (a simple DC circuit in an introductory circuit course) through a structured and guided hands-on activity could significantly improve their self-perceived problem-solving skills, which indicates that integrating more similar training and activities into the curriculum has a great potential in improving students' confidence and proficiency in troubleshooting.

The results depicted in Figure 7 reinforce the insights gained from Figure 6, highlighting the positive reception of the lab activity. Notably, over 65% of students strongly recommended expanding the activity to other courses with laboratory components, indicating a widespread appreciation for its value in skill development. In contrast, only 11% of students expressed neutrality, reflecting uncertainty about the activity's impact or its broader applicability. It is evident that the majority of the surveyed students had become aware of the importance of troubleshooting skills in engineering practice by the end of the lab exercise, although it is unknown if such awareness was developed as the result of the troubleshooting activity. More importantly, they saw

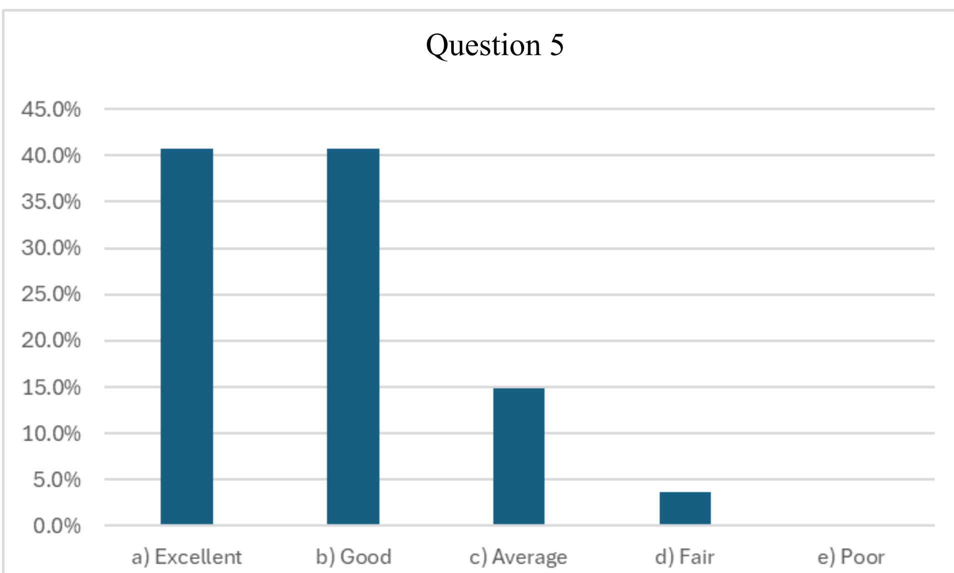

Figure 6: *Survey results for question 5*

a pathway through this exercise to acquiring and strengthening such skills and thus recommended to incorporate similar activities in other related courses. With the troubleshooting activities expanded across courses throughout the curriculum, students would be provided with abundance of opportunities to develop these critical skills in various contexts through a consistent framework and thus potentially be more ready for real-world challenges.

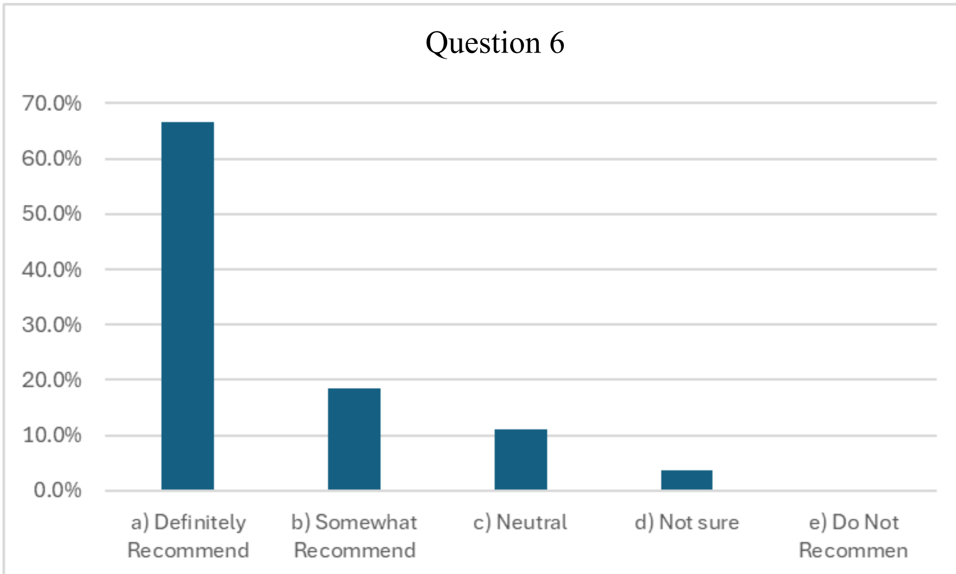

Figure 7: *Survey results for question 6*

Conclusions

A troubleshooting laboratory activity was developed, implemented, and deployed in a sophomore-level circuit course to enhance undergraduate engineering students' troubleshooting and problem-solving skills, addressing the growing demand for soft skills by Industry 5.0. The laboratory exercise requires students to proactively take part in a troubleshooting task, which involves identifying and correcting the mistakes that were intentionally introduced into a DC circuit. Although the work is still in its early stage, the feedback from the students surveyed has been overwhelmingly positive and encouraging. The survey data reveals that, from students' perspective, the designed activity is effective in not only developing and reinforcing troubleshooting skills but also strengthening their understanding of the underlying theories. Furthermore, the majority of the surveyed students supported the idea of adapting the laboratory exercise to be applied to other technical courses, creating a thorough line in the curriculum that parallels the progression of the technical content.

To achieve the ultimate goal of establishing a structured, easily adaptable, and assessable framework for a broader application of the pedagogical approach pursued by this work in the ECE curriculum, a two-stage process that is based off the insights gained from the survey data analysis is proposed as follows. The first stage focuses on updating the existing troubleshooting exercise in the same introductory circuit course, which includes:

1. Converting the assignment from group to individual effort to make the exercise more challenging, equalize engagement among all students, and more accurately assess its effectiveness. Assigning the troubleshooting exercise as an individual activity in the current small classes will require the creation of additional pre-made circuits, allowing the activity as a group effort to be scaled up for a larger class size.
2. Developing assessment mechanisms to evaluate the correlation between students' satisfactory level and the effectiveness of the exercise in improving their troubleshooting skills. The assessment results shall be derived not from students' perception but the objective evaluation of their performance in another related exercise. For instance, a comparison study could be run among multiple sections of the same course in the same semester, which entails (1) deploying the troubleshooting exercise in half of the sections, (2) administering an individual laboratory final exam in all sections where all students are asked to independently construct and test a DC circuit, and (3) comparing the lab final average of the sections that are assigned with the troubleshooting exercise with that of those that are not. Another place we could draw insight from is the ABET assessments that have been conducted every year, specifically those for the outcomes on solving engineering problems, by tracking if the attainment rate of those outcomes improves with the deployment of the troubleshooting exercise.

In the next stage, the focus shifts to the adaptation and application of the same pedagogical practice to other technical courses in the ECE curriculum, which will involve:

3. Developing similar troubleshooting laboratory exercises to be introduced to upper-level circuit courses to expand students' troubleshooting skillset for AC circuits that contain linear and/or non-linear electronic components. Additionally, troubleshooting skills can be easily adopted in programming courses, where students would be provided with pre-written code in languages such as C, C++, or Python and asked to identify and debug the intentionally introduced bugs.
4. Achieving faculty buy-in within the ECE programs for (1) incorporating more open-ended questions into written and/or hands-on exercises and (2) developing troubleshooting-centered exercises for their respective technical courses at all levels so that our students would be consistently engaged in meaningful problem-solving throughout the curriculum. These exercises will reinforce troubleshooting skills in the classroom beyond laboratory sessions, helping build a solid foundation for enhancing problem-solving abilities not only across the ECE curriculum but across all engineering programs.

With the modifications as suggested in the second stage successfully implemented, the authors believe that our students will be better prepared for the challenges of Industry 5.0 and equipped with strong technical and soft skills that are essential for future academic and professional success.

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