Circuit Troubleshooting Based on Applying Lean Six Sigma Techniques

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Abstract

This paper presents Lean Six Sigma techniques and methods that Electrical Engineering Technology (EET) students have found useful in their in-class circuit troubleshooting activities. When students are first learning circuit analysis and fabrication, they often lack the skills to troubleshoot failed circuits based on a specification. In addition to presenting the tools used in the instruction of the test student group this paper also describes how the Lean Six Sigma method were used to arrive at the optimal course content.

For this paper, two student groups, in an EET laboratory experience, are compared based on the primary metric number of failed attempts to meet circuit board test specifications. The student test body was divided into two groups. A control course section group, where no troubleshooting instruction was given and designated the “As Is” state. The second section group, “Improved State” was given an extensive troubleshooting methodology as part of their initial training. The primary metric, number of failed attempts to meet specification, was chosen as it is easy to measure by student Teaching Assistants (TA) and was also used to assess the Sigma process capability for each group. The Sigma capability of each group provided a further measure of the overall success of the intervention.

The authors quickly realized that students in the control group were making two classic types of errors. Many students were making a rule or knowledge-based error, where students were not following the instructions for the specific circuit fabrication and test. This type of error was addressed by improving instructional material and adding root-cause analysis checklists to the course content. The second type of observed error, where a student is incorrectly applying a base skill to the construction protocol, is classified as event-based and is more difficult to resolve. Theoretically, there can be many possible solutions to an event based error. Perhaps there may even be no optimal solution to the error, or “right answer,” just a work around that students must find. To address this type of error students were instructed how to apply Lean Six Sigma tools such as root-cause analysis and Failure Modes and Effects (FMEA) matrices in their problem-solving sessions. Also, Sneak Analysis was included to address typical design flaws.

Introduction

The course targeted for this project is ECET 10700 - Introduction to Circuit Analysis. This course teaches dc circuit analysis and laboratory skills to freshman electrical, computer and healthcare management engineering technology students. The students have already demonstrated competency in college algebra, and during the last part of the course are able to apply trigonometric functions in the context of reactance calculations. They have had previous instruction in problem identification, computer applications for calculations and graphing, and laboratory report writing.

For some of the students, the lab assignment targeted in this project is the first time they have measured resistance, current or voltage in the laboratory.   During the lecture, they have learned about the concepts of resistance, current, and voltage. They have been introduced to Ohm's Law, and have been instructed that an ammeter should be in line with the current to be measured. However, it is during this lab period that they will test their understanding of these concepts in a practical way.

The instructions for this lab assignment begin by having the students locate three resistor values and verifying their values and tolerance. Then the students are instructed to build the circuit in Figure 1. This circuit is simply a resistor mounted in series with a dc voltage supply and dc ammeter. The dc voltage measured across the resistor should be the same as the voltage supply.

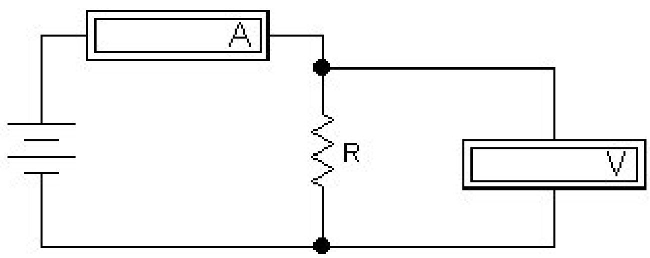

Figure 1 Circuit for Laboratory Assignment

The objective of the assignment is to verify Ohm's law by graphing the current-voltage relationship for three different resistors.

Over several semesters, instructors and teaching assistants have noticed a variety of mistakes students make during this assignment. When students struggle with equipment and circuit connections, they grow frustrated and cannot meet the objectives of the lab assignment. We were looking for a way to improve student performance during the circuit building and measurement components of laboratory assignments.

The Rapid Lean Six Sigma, Kaizen, process management method was utilized to provide a framework for the entire project management process. Kaizen is a Japanese word that describes the concept of continuous process improvement that involves all branches of a facility or company and is typically associated with the rapid or intense activity and workflow. The Kaizen method of managing events is now part of every Lean Six-Sigma facilitators toolkit. Kaizen is most effective if the specific issue or project solution is known, easy to find, or can practically be described as a "quick hit." Typically a Kaizen event will last for 3-5 days where most of the time is spent in preparation for the trial solution event that may only last a matter of hours. Figure 2 illustrates the process steps and requirements for a Kaizen event that was followed throughout this project.

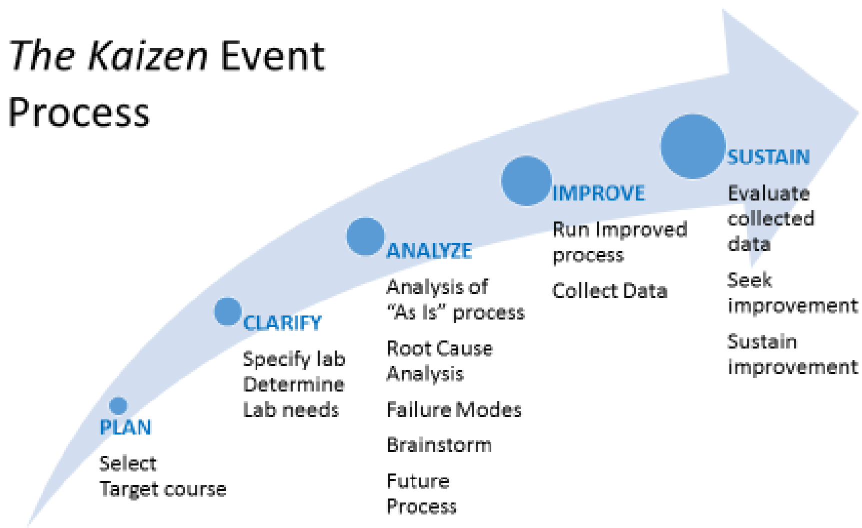

Figure 2 The Kaizen process overview

One of the project goals is to provide mistake proofing and prevention tools that our students can use not only within the confines of this laboratory experience but also be part of their troubleshooting arsenal that can be applied to future courses and jobs. To address this requirement another Lean Six Sigma tool referred to as Poka-Yoke (error prevention) was inserted into the Kaizen event. The Kaizen event, Figure 2, can be viewed as the high-level process and the Poka-Yoke tool is the structured problem-solving technique applied to the problem. Poka-yoke (poh-ka –yoh-kay) was developed by Shigeo Shingo as part of the Toyota Production System, or ZQC, Shingo's Zero Quality Control System. The idea of this system is to have sufficient detection mechanism such that mistakes are prevented from occurring and propagating through the manufacturing process. The Poka-Yoke technique requires that both mistake prevention, the ability to stop mistakes from occurring, and mistake proofing, making it impossible for a mistake to occur, must be addressed simultaneously. There is no universally accepted procedure for Poka-Yoke; however, the eight steps that follow are generally accepted as fulfilling the basic requirements of this technique.

Step 1: Describe the Problem

- Create a clear, complete problem statement. Describe how it impacts the customer.

Step 2: Use a Team Approach to ID the process and process step causing the error

- Construct a process flow diagram and identify the point of deviation.

Step 3: Contain the problem

- Always stabilize the current situation.

Step 4: Find the Root Causes .

- Techniques to search for the root cause can include:
    - The Five-Whys
    - FMEA

- Data Collection plus Analysis
- Design of Experiments (DOE)

Step 5: Develop Mistake-Proofing Solutions

- Use the Brainstorming technique to find possible solutions.
- Always think outside of the box.
- Do your solutions work in practice?

Step 6: Implement the Solution

- Apply a simple action plan.

Step 7: Prevent Errors From Occurring Again

- Test the solution; make sure the solutions work.
- Is the solution is robust or does it need to be simplified?

Step 8: Congratulate the Team

We held a Kaizen event, including the students and teaching assistants, aimed at improving student performance when building circuits and collecting voltage and current data.

Experimental procedure

Although the faculty have been aware that students struggle in lab, no data had been collected that would identify and quantify the types of student mistakes associated with this assignment. Therefore, an experienced lab instructor listed typical student errors for each part of the assignment. This list of common errors was transferred to a tally sheet for data collection. (See Figure 3 for an excerpt.)

Table 4 OBSERVATION	ERROR	Number
The DMM (ammeter) reads 0 mA	Ammeter incorrectly located	
	Ammeter lead incorrectly ported	
	Ammeter fuse blown	
	Power supply issues	
The voltage indicated at the power supply is less than that expected, and the current reading on the power supply is 1.0 A	Circuit built incorrectly	
	There is a short across the resistor	
	Ammeter is installed across resistor	
Voltage indicated is different from that calculated	Resistor value is incorrect	
Resistance calculated is off by more than the 10% expected.	Indicated voltage error	
	Calculation error	

Figure 3 Excerpt from tally sheet

Two laboratory sections were used in this experiment: the control group met on Wednesday, and the intervention group on the following Monday. The tally sheets were used by the instructor and teaching assistants during the Wednesday lab period to quantify the students' issues. After the lab period, the data was evaluated, and the prevalent types of mistakes were identified. Two days later, during the Friday recitation period, the authors led all the students in a process mapping activity (see below). On the following Monday, the intervention laboratory section was observed and student issues were tallied.

Intervention

Between the lab periods of the control group (Wednesday) and the experimental group (Monday), the class in-total meets for a recitation period (Friday). These meetings are led by undergraduate teaching assistants who also support students in the laboratory. The recitation topics are selected by the course instructor and TAs in conference and vary based on the week's objectives: organizing parts kits, practice problems, test review, and general concept questions.

At beginning of the recitation session, the class met together for approximately ten minutes for an introduction to Structured Mistake Proofing and Prevention, process mapping and instructions on the activity.

Students were divided into pre-determined groups of approximately eleven students each; two groups were from Wednesday lab (A and B) and two groups were from Monday lab (C and D). Each group was facilitated by one of the authors or teaching assistants. Groups A and C met in one class room, and B and D moved to another room.

The first activity was to create a process flow diagram for the lab assignment. Students brain-stormed (See instructions given in Figure 4) process steps and wrote each step on a sticky-note. Examples included:

- Find parts
- Test power supply
- Connect ammeter
- Read assignment
- Record current
- Verify wiring

How to Brainstorm

1) Clearly, understand the problem and formulate a simple question based on the problem
2) Clarify the goal of the event
3) Spend two minutes generating at least five ideas and write each on a sticky note.
4) After two minutes place your sticky notes onto the event board
5) As a group, review your results. Repeat the brainstorming as many times as possible.
6) Spend another few minutes generating more ideas and placing each onto the event board
7) As a group search for duplicate ideas. Place the best interpretation on top of idea stack.
8) After searching for duplicates your group should affinitize (group) the ideas.
9) Filter your results.

Figure 4 Instructions provided

After students had affinitized their process step suggestions, they arranged the sticky notes into a process flow diagram, adding flow arrows as needed. An example process flow diagram is shown in Figure 5.

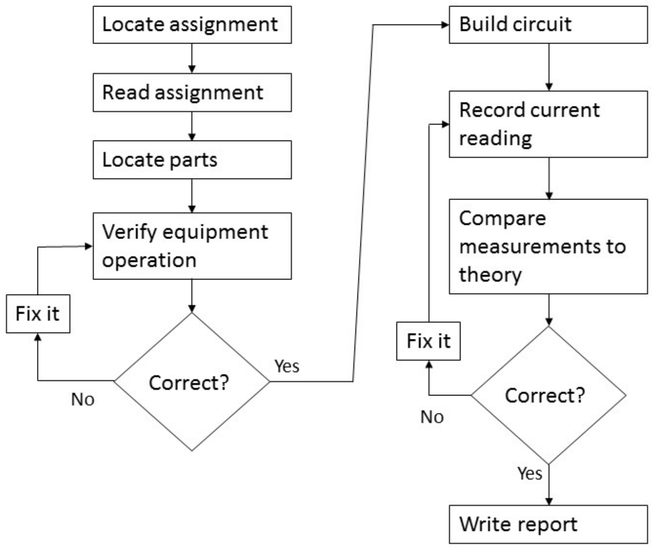

Figure 5 Example Process Flow Diagram

The next activity for each group was to identify possible errors that might arise. The groups discussed likely errors and what might be done to prevent them.

After 30 minutes of working in groups of eleven, the two groups in each room came together to compare their process flow charts, identify the best of each, and combine them into one chart to represent the contributions of the 22 students in room. Then all 44 students met to review the two representative process flow charts and suggestion on how to "mistake proof" the lab experience.

The final two process flow charts were similar, although still unique. The authors instructed the students on the process used in manufacturing to "kit" parts before beginning assembly. Students then offered practices for mistake proofing. Some offered general ideas such as "Pay more attention" and others gave specifics about improving wording of instructions.

For the Monday intervention group, three changes were made. First, students were given a template to assist in "kitting" the parts needed for the assignment. This turned out to be less impactful for this particular assignment, since students had measured the resistors in their personal parts kits, and did not need to draw any parts from inventory. Second, students were encouraged to "color code" the wires used to create the circuit, visually linking the lines in the schematic to the physical circuit. Third, instructions were clarified by posting a question to the students during the lab period: "Does the circuit need to be changed between parts 2 and 3?" This required the students to compare the schematics presented in each part and recognize the similarities and differences, reducing errors introduced by changing the circuit.

Results

The following results and analysis combine all data collected over the entire process improvement project. It shows that the specific interventions strategies applied to the Monday intervention group resulted in a 75% reduction in errors per student when compared to the Wednesday control group.

The results and analysis presented in this section are based on the following assumptions:

a) That students worked independently in pairs constructing and testing their assigned circuit board. This ensures that we can count each student pair as an independent unit in our calculation of errors as defects per unit (DPU).

b) That there were 22 student pairs in total participating in this study. 11 student pairs (units) in the Wednesday, control section, and 11 different student pairs participating in the Monday, intervention laboratory section.

c) The Wednesday laboratory section was not aware of the interventions that were applied in the Monday laboratory section. Therefore, it is reasonable to assume that the control group worked independently from the intervention group.

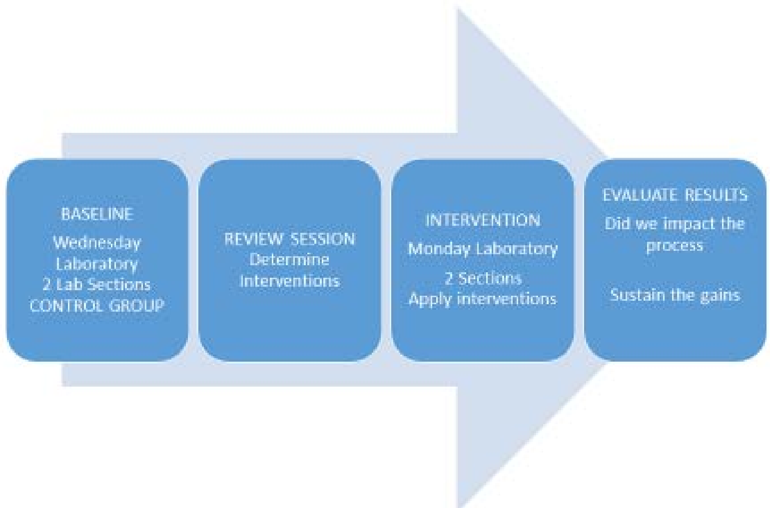

Figure 6 High-level process map of project action items presented as a timeline.

This entire process of data collection and analysis can best be described using a high-level process map, Figure 6, and the assumptions based on the division between the control and intervention group division is given in Table 1.

Table 1 Student Group, group size, and laboratory meeting time.

Student Group	Number of Students	Laboratory Meeting Day	Total Error Count
Control	22	Wednesday	**29**
Intervention	22	Monday	**7**

Based on expert opinion the number of opportunities for errors per student (unit) circuit board construction and testing procedure was determined to be 29 (Opportunities for defects per unit, OPU). The total numbers of errors (defects) for the Wednesday and Monday laboratory meetings were 29 and 7 respectively, Tables 1 and 2. Table 2 is an abbreviated version of the error checklist used by the instructor and teaching assistants during the Monday and Wednesday laboratory meetings. It lists the specific data collection table used in the laboratory experiment, the observation the student would expect to see if there were an error and the actual cause of the error by category. Teaching assistants and instructor were instructed to tally each error in the correct error category.

Table 2 Comparison of Observation, error category and tally for Wednesday and Monday laboratory sections

Table	Observation	Error	Control (Wednesday) Error Count	Intervention (Monday) Error Count
3	The DMM (ammeter) reads 0 mA	Incorrect Connection	2	0
3	The measured value is off by a factor of 1000	Student reading meter incorrectly (kohms)	2	1
3	The measured value is off by a factor of 1000	Misread resistor color code	0	1
3	The measured value is off by more than 5%	Misread resistor color code	3	0
3	The measured value is off by more than 5%	Calculation error	2	0
4	The DMM (ammeter) reads 0 mA	Ammeter incorrectly located	3	1
4	The DMM (ammeter) reads 0 mA	Ammeter lead incorrectly ported	3	0
4	The DMM (ammeter) reads 0 mA	Power supply issues	3	0
4	The DMM (ammeter) reads 0 mA	Ammeter fuse was blown	0	1
4	The voltage indicated at the power supply is less than that expected, and the current reading on the power supply is 1.0 A	Circuit built incorrectly	1	0
4	The voltage indicated at the power supply is less than that expected, and the current reading on the power supply is 1.0 A	Ammeter is installed across resistor	0	2
4	Resistance calculated is off by more than 10% expected.	Calculation error	3	1
5	DMM (ammeter) reads incorrect value	Circuit built incorrectly	7	0
		TOTAL	29	7

Clearly, the errors were not uniformly distributed across all the opportunities as observed from the tally distribution in Table 2. Pareto analysis of the same data for the Wednesday group gives a clear picture of the distribution of error categories, Figure 7, that assisted the mistake proofing and prevention review.

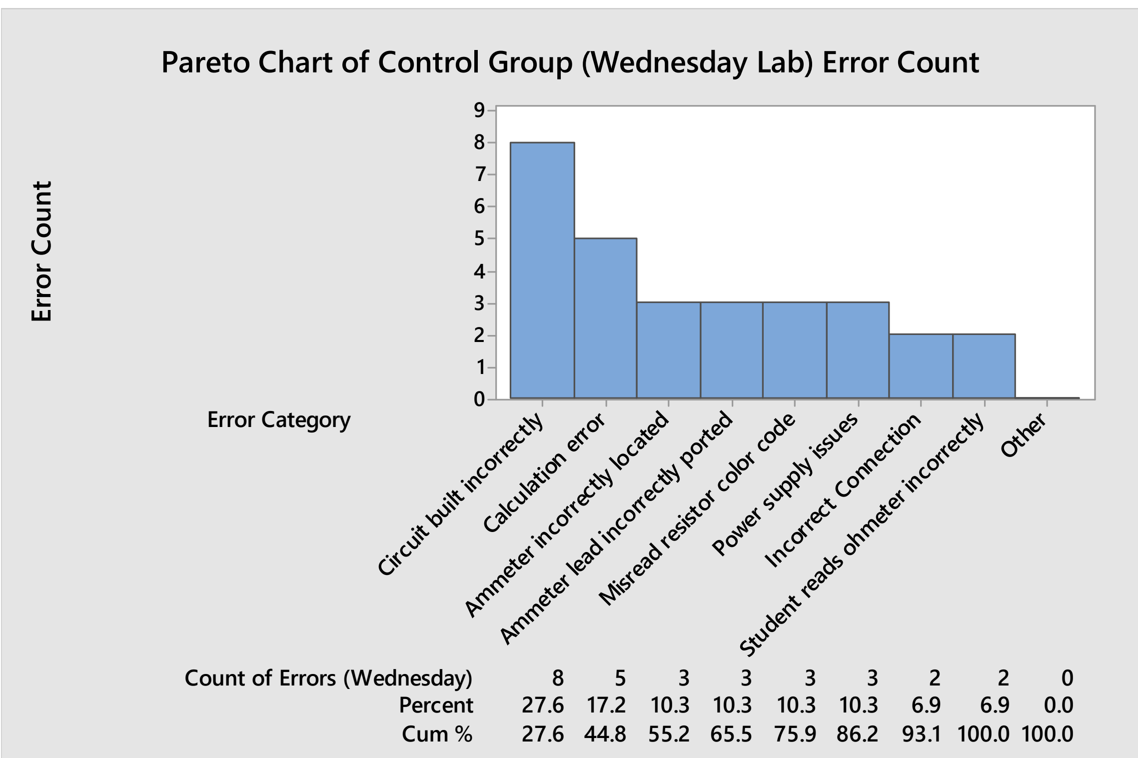

Figure 7 Indicating the Error count in order of occurrence for the Wednesday laboratory section

In the recitation session that took place after the Wednesday laboratory, all students and teaching assistants participated in a brainstorming and process flow diagram session that resulted in a simple list of intervention strategies. The interventions were implemented during the Monday laboratory session, and the same checklist and tally sheets were used to collect error data. Defects per unit (DPU), and Defects per Million Opportunities (DPMO) metrics were then calculated to compare both the intervention and control groups. DPMO were calculated as follows:

$$DPMO = \frac{Defects/Unit}{Opportunites/Unit} \times 10^6$$

The resulting comparison of Wednesday (control group) compared to Monday (intervention group) DPU or DPMO indicates a 75% reduction in individual student errors, Table 3. As the same error categories were repeated in the checklist by table and observation, a combined error category table was generated for both the intervention and control groups tally sheet, Table 4. A 2 Sample Poisson test of Defects per Unit (DPU) indicate that the DPU of the intervention group was statistically significantly less than the Wednesday intervention group at the 95% confidence level (alpha = 0.05).

Table 3 Comparing DPU and DPMO for the Wednesday and Monday laboratories

Laboratory Group	Defects per Unit DPU	Defects per Million Opportunities DPMO
Wednesday	$\frac{29\ errors\ counted}{11\ student\ pairs} = 2.64$	$\frac{2.64}{29} \times 10^6 = 910344$
Monday	$\frac{7\ errors\ counted}{11\ student\ pairs} = 0.64$	$\frac{0.64}{29} \times 10^6 = 220689$

Table 4 The Error count based on error category only, used in 2-Sample t-Test.

Error Category	**Control (Wednesday) Error Count**	**Intervention (Monday) Error Count**
Ammeter fuse was blown	0	1
Ammeter incorrectly located	3	1
Ammeter is installed across resistor	0	2*
Ammeter lead incorrectly ported	3	0
Calculation error	5	1
Circuit built incorrectly	8	0
Incorrect Connection	2	0
Misread resistor color code	3	1
Power supply issues	3	0
Student reading meter incorrectly (kohms)	2	1
TOTAL	**29**	**7**

* Additional research is needed to determine why the intervention group struggled with aspect of the lab assignment.

Although the sample size was small (n < 15) for this preliminary study the results are very encouraging and therefore will be repeated in other laboratory sections and courses.

Conclusions

The results show the error count from the laboratory section following the intervention is statistically significantly less than in the laboratory section before the intervention. The teaching assistants and instructor credit the intervention during the Friday recitation with the improvement. Because of the discussion of the kitting instructions, students remembered to bring their own parts kits, and teaching assistants knew to instruct students to check values for any borrowed components. Assignment instructions were clarified. Students came to lab more familiar with the circuit and the process to build it. All these effects contributed to prevent mistakes in the process.

To sustain these improvements, the revisions to the lab assignment will be made permanent; the instructor and teaching assistants will look for clarifications in other assignment instructions. In the future, students will be asked to anticipate failure modes and how to prevent them as part of the pre-laboratory assignment, then reflect on those predictions in lab report conclusions. Training on other Lean Six Sigma techniques will be included in the curriculum.

This project demonstrates that even a brief, 75 minute Kaizen event held for freshman circuits students can improve their laboratory performance. Future work will examine if the intervention during this early lab assignment impacts performance later in the semester during a laboratory practical examination.

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