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Application of Gauge Repeatability and Reproducibility in Root Cause Analysis of Electronics Problems in an Engineering Technology Course*

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Gauge Repeatability and Reproducibility (Gauge R&R) is a useful skill needed in industry. Engineers rely on data to do analysis such as finding the root cause of a problem. Before data collection, the measurement system used to collect data must be analyzed first. Gauge R&R is a measurement system analysis (MSA) tool. This paper discusses the learning of Gauge R&R by engineering technology students. A laboratory exercise followed the introduction of the concept in a lecture. Students were tasked to create an Excel program to implement the Gauge R&R analysis. Test data were collected and analyzed using the Excel program they created. Gauge R&R was used as a tool for finding the root cause of a problem where the resistance measurement data were inconsistent. The learning module of a combination of lecture, laboratory, and data analysis worked well for engineering technology students. Self-evaluations before and after the learning module from eighty three participants indicate that students believed that they learned the subject well.

Keywords: Gauge R&R; root cause analysis; six sigma; student learning

1. Introduction

Since the 1980s, educators have realized the importance of statistics to engineering education [1–5]. Today, it is widely accepted in academia and industry that the application of statistics in design, testing, and data analysis is a necessity for companies to maintain their competitiveness in the global market. Driven by the needs in industry, statistics education enhancement in engineering and engineering technology programs has been extensively studied [1, 5, 6–16]. Different approaches for statistics curriculum enhancement for engineering and engineering technology programs have been proposed. Barton et al. [10] and Standridge and Marvel [13] proposed to use laboratory extensively for learning statistics. Using actual data collected by students for statistical analysis was proved to be an effective method [9]. Extensive use of software such as Excel, MATLAB, and Minitab can increase student learning of statistics [17, 18]. Zhan et al. attempted to apply statistical analysis tools in several engineering technology courses instead of teaching these in a separate applied statistics course [16]. Applications of statistics in specific problems allow students to make the connection between statistics and their major.

One of such statistical analysis tools is Gauge Repeatability and Reproducibility (Gauge R&R), which is often used to analyze the accuracy of a measurement system, part-to-part variation, and variation due to the technicians taking the data. It is a practical and useful tool for engineers and technicians [19]. With the help of software such as Excel and Minitab [20], Gauge R&R analysis has become straightforward.

Many research results related to Gauge R&R can be found in the literatures [21–35]. Gauge R&R is also used in Lean Six Sigma projects as a part of the measurement system analysis [36–38]. Since Lean Six Sigma emphasizes statistical data analysis, it is critical to ensure that the Gauge R&R analysis is carried out before data are collected.

In addition to the research interests related to Gauge R&R, it was also found that there was a high level of interests in using Gauge R&R in industry and other sectors. Simion presented a case study on Gauge R&R in automotive industry [39]. Erdmann et al. carried out a Gauge R&R analysis in a hospital [40]. There were several other successful uses of Gauge R&R in Lean Six Sigma projects [41–43]. Rosenkrantz conducted a survey to automotive executives in the USA to assess the importance of some quality tools and statistical methodologies commonly used in industry [44]. More than 70% of the 306 responses listed Gauge R&R as the methodology most often used by their organization. This percentage was the highest among the seventeen quality tools and statistical methodologies evaluated in the survey.

The Society for Manufacturing Engineers identified Gauge R&R as a required competency for manufacturing engineers [45, 46]. For this reason, many mechanical engineering programs included Gauge R&R in their curriculum [11, 47–49]. Often times, the measurements are physical quantities

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such as dimensions and weights [50]. However, Gauge R&R analysis is not limited to such measurement systems. For instance, encouraging results were reported by Korestky when Gauge R&R was taught to chemical engineering students [51]. Zhan found that Gauge R&R was just as relevant for electronic engineering technology student when voltage, resistance, and inductance were measured [52]. For many engineering and engineering technology students, the most important aspect of Gauge R&R is the concept of variations in measurements, which is a paradigm shift from dealing with nominal values and finding a unique solution in homework problems in typical engineering courses.

Gauge R&R is one of the topics taught in a sophomore course "Six Sigma and Applied Statistics" (ESET 329) offered by the Electronic Systems Engineering Technology (ESET) program in the Department of Engineering Technology and Industrial Distribution at Texas A&M University. Based on the literature review, a learning module consisting of a lecture, laboratory testing, and data analysis was created for students to learn Gauge R&R.

The Bloom Taxonomy for student learning categorized learning into six areas: remembering, understanding, applying, analyzing, evaluating, and creating [53]. The lecture part of the Gauge R&R module addresses the first two categories, i.e., remembering and understanding. A laboratory exercise after the lecture provides students with opportunity to apply Gauge R&R and analyze the root cause of a problem. Therefore, four of the six categories of Bloom's Taxonomy for student learning were involved in the learning module.

The detailed implementation of the module is discussed in this paper. Section 2 presents the theory of Gauge R&R, which is taught in a lecture. In section 3, the laboratory part of the module is discussed. The laboratory part includes data collection and data analysis using software programming. Assessment of student learning is presented in section 4. Section 5 contains discussions. The conclusions and future work are presented in Section 6.

2. Teaching the theory of Gauge R

The concepts of repeatability and reproducibility (R&R) were introduced in a lecture. Repeatability is the ability to repeat the same measurement by the same operator at or near the same time [36, 37]. Reproducibility is the ability to produce the same result by different operators at different times [36, 37]. There are four major factors contributing to the measurement error: operator, part, the interaction between the operator and part, and accuracy of the measurement system. The ANOVA (Analysis of variance) is the most popular and accurate method for analyzing repeatability and reproducibility and interactions between the operators and the parts. The procedure of Gauge R&R analysis was introduced first:

1. Randomly choose L parts to be tested.
2. Identify the parts by numbering them from 1 to L.
3. Pick N technicians/inspectors.
4. Have the technicians randomly measure the parts using the same measurement system.
5. Repeat step 4, M times, so that you have replications for each technician/part combination.
6. Conduct Gauge R&R analysis.
7. Determine the next step based on the Gauge R&R analysis result.

In a lecture and the lecture notes posted in eCampus, the formulas for Gauge R&R [37] were provided to the students. These were later used in the laboratory to create an Excel program for implementation of Gauge R&R analysis.

Let the k-*th* measurement of part j, taken by team i be denoted as $X_{i,j,k}$, $i = 1,2,\ldots,N$, $j = 1,2,\ldots,L$, $k = 1,2,\ldots,M$. The sum for the measurement taken by team i is defined as $TeamSum_i$

$$TeamSum_i = \sum_{j=1}^{L}\sum_{k=1}^{M} X_{i,j,k}, \quad i = 1,2,\ldots,N \quad (1)$$

Let n_1 be the number of measurements each team took and n_2 be the number of measurements taken for each part, then

$$n_1 = ML,\ n_2 = MN \quad (2)$$

The average measurement value of team i, $TeamAvg_i$, is calculated as follows

$$TeamAvg_i = \frac{TeamSum_i}{n_1}, \quad i = 1,2,\ldots,N \quad (3)$$

The sum of the average of team i's total measurements squared, $SumColSq$, is calculates as follows

$$ColSq_i = \frac{TeamSum_i^2}{n_i}, \quad i = 1,2,\ldots,N, \quad (4)$$

$$SumColSq = \sum_{i=1}^{N} ColSq_i \quad (5)$$

For part j, the sum of all measurements, $PartSum_j$, is calculated as follows

$$PartSum_i = \sum_{i=1}^{N}\sum_{k=1}^{M} X_{i,j,k}, \quad j = 1,2,\ldots,L \quad (6)$$

The average measurements for part *j*, $PartAvg_j$, is calculated as follows

$$PartAvg_i = \frac{PartSum_j}{n_2}, \quad j = 1, 2, \ldots, L \tag{7}$$

The sum of the average of part *j*'s total measurements squared, *SumRowSq*, is calculated as follows

$$RowSq_j = \frac{PartSum_j^2}{n_2} \tag{8}$$

$$SumRowSq = \sum_{j=1}^{L} RowSq_j \tag{9}$$

The sum of all measurements taken, *SumX*, can be calculated two different ways

$$SumX = \sum_{i=1}^{N} TeamSum_i = \sum_{j=1}^{L} PartSum_j \tag{10}$$

In the implementation, this can be used a check in students' Excel program so that potential mistakes in coding can be identified early.

The sum of all measurement squared, *SumXSq*, is calculated as follows

$$SumXSq = \sum_{i=1}^{N} \sum_{j=1}^{L} \sum_{k=1}^{M} X_{i,j,k}^2 \tag{11}$$

The sum of the average of repeated measurements sum squared, *SumInteractSq*, is calculated as follows

$$InteractSq_{i,j} = \frac{(\Sigma_{k=1}^{M} X_{i,j,k})^2}{M} \tag{12}$$

$$SumInteractSq = \sum_{i=1}^{N} \sum_{j=1}^{L} InteractSq_{i,j} \tag{13}$$

The correction factor for mean, *CM*, is calculated as follows

$$CM = \frac{SumX^2}{M \times N \times L} \tag{14}$$

The total sum of squares, *TotSS*, is calculated as follows

$$TotSS = SumXSq - CM \tag{15}$$

The sum of squares for teams, *TeamSS*, is calculated as follows

$$TeamSS = SumColSq = CM \tag{16}$$

The sum of squares for parts, *PartSS*, is calculated as follows

$$PartSS = SumRowSq - CM \tag{17}$$

The sum of squares for interaction, *InterSS*, is calculated as follows

$$InterSS = SumInteractSq - CM - TeamSS - PartSS \tag{18}$$

The error sum of squares, *ErrorSS*, is calculated as follows

$$ErrorSS = TotSS - TeamSS - PartSS - InterSS \tag{19}$$

The degree of freedom for teams is *N-1*. The degree of freedom for parts is *L-1*. The degree of freedom for interactions is *(N-1)(L-1)*. The total degree of freedom is *NML-1*. The degree of freedom for error, ErrorDF, is calculated as follows

$$ErrorDF = Total\ DF - Team\ DF - Part\ DF - Interaction\ DF \tag{20}$$

The error, team, part, and interaction mean squares are calculated as the ratios of sum of squares and the degree of freedoms

$$MS = SS/DF \tag{21}$$

The F-test statistics, *Fcal*, is calculated as follows

$$Fcal = MS/ErrorMS \tag{22}$$

This test statistics is compared to the *F*-critical value with certain confidence level. Typically, 95% confidence level is used. If the *F*-test statistics is greater than the *F*-critical value, then one can conclude that there is significant variation in the corresponding category.

The variances for teams, parts, and interactions are calculated as follows

$$Var_{Team} = \frac{TeamMS - ErrorMS}{N \times L} \tag{23}$$

$$Var_{Part} = \frac{PartMS - ErrorMS}{N \times M} \tag{24}$$

$$Var_{Int} = \frac{IntMS - ErrorMS}{M} \tag{25}$$

The variances are adjusted so that any negatives value will be replaced by 0. The total variance, *TotVar*, is calculated as follows

$$TotVar = adjVar_{Team} + adjVar_{part} + adjVar_{int} \tag{26}$$

The percentage contributions from team, part, interaction and error are calculated as follows

$$\%Var_{Team} = \frac{adjVar_{team}}{TotVar} \times 100\% \quad (27)$$

$$\%Var_{part} = \frac{adjVar_{part}}{TotVar} \times 100\% \quad (28)$$

$$\%Var_{int} = \frac{adjVar_{int}}{TotVar} \times 100\% \quad (29)$$

3. Using Gauge R&R to find a root cause of a problem

Applying the theory in practical problems requires higher level learning. This is particularly true for engineering technology students since for them hands-on learning is the focus. There were several reports on the effectiveness of student learning using laboratory-based approach [10, 13]. Therefore, the laboratory component development was the focus of the Gauge R&R learning module.

The first decision to make was what software to use for Gauge R&R analysis. There were several options:

1. Using Minitab software [20].
2. Using free online program written in Excel, such as the one developed by QIMacros [54].
3. Developing an Excel program by the students following an example for Gauge R&R implementation written by the instructor.

Each of these options has their advantages and disadvantages, these are summarized in Table 1.

These options were tried out in the first two semesters of the offering of the course. Based on student feedback and the observations made by the instructor in the laboratory, the final approach was a combination of using Minitab and developing Excel program by students. This approach allows for comparison of the results from the two methods and involves higher level of learning.

The laboratory exercise was to use digital multimeters of the same type to measure the resistances of ten resistors with the same nominal value. Students were divided into teams to take turns to measure the resistances. A simple example of Excel implementation of Gauge R&R analysis was provided to students. Students were tasked to go through the Excel program example in the prelab to understand how the formulas were implemented. The example Excel program would only work for specific values of *M, N*, and *L*. So, students could not just copy and paste the test data to complete the Gauge R&R analysis. They must write their own Excel program for different *M, N, L* values after they fully understand the implementation in the example. A part of the Excel program and the code are shown in Fig. 1. The last column in Fig. 1 has the contributions from teams, which is the reproducibility, and from measurement error, which is the repeatability. R&R is the sum of these two terms. If the Gauge R&R contribution is more than nine percent, the measurement system is deemed as unacceptable [36].

Students first worked on their Excel program for GR&R analysis for a given set of values with $M = 5$, $N = x$, and $L = 10$, where x is the number of teams. Since the value of x varies from one semester to the next, the program cannot be copied from one semester to the next. A set of data with appropriate size was provided to the student teams. The solution to this Gauge R&R analysis problem was worked out by the instructor or TA beforehand. This solution was used to check each student team's Excel program. Only teams with the correct answer were allowed to move onto the data collection stage. They took multiple resistance measure-

Table 1. Comparison of the three options

Options	Advantages	Disadvantages
Using Minitab	It is easy to use; the whole process of Gauge R&R requires a series of clicking of buttons. The users don't need to deal with the details of the calculations; they just need to know how to import the data and how to explain the analysis results. Knowing how to use Minitab is a useful skill.	The users do not understand the underlying calculations required by the GR&R analysis. The users completely rely on the availability of the software. They do not have the option of checking intermediate results. If something appears to be wrong, it is not easy to troubleshoot. There is no high level learning involved.
Using free online program	It is even easier than Minitab; it is all about copying and pasting of the raw data. The users don't need to know how the calculations are done; they just need to know how to explain the analysis results.	There is no high level learning involved. The details of the calculation are protected and not visible to the users. The users do not have the option of checking intermediate results. If something appears to be wrong, it is not easy to troubleshoot.
Developing an Excel program by the students	Students must understand the steps in Gauge R&R analysis. It involves higher level of learning in the Bloom's category of applying. Intermediate results are available for troubleshooting. It is easy to add more features if necessary.	It takes longer time to implement and is more likely to make a mistake.

R	S	T	U	V	W	X	Y	Z
					ANONA Table alpha=		0.05	
Source	SS	DF	MS	Fcal	F(alpha)	Var	Adj Var	%
Team	0.62	2	0.31	1.28	3.68	0.007	0.01	1.08
Part No.	9.87	4	2.47	10.21	3.06	0.371	0.37	59.89
Interaction	1.63	8	0.20	0.84	2.64	-0.019	0.00	0.00
Error	3.63	15	0.24			0.242	0.24	39.03
	total DF	29				totals	0.62	100.00

R	S	T	U	V	W	X	Y	Z
					ANONA Table alpha=		0.05	
Source	SS	DF	MS	Fcal	F(alpha)	Var	Adj Var	%
Team	=P4	=E3-1	=S3/T3	=U3/U6	=F.INV(1-Y$1,T3,T$6)	=(U3-U6)/C15	=IF(X3>0,X3,0)	=Y3/Y7*100
Part No.	=P5	=A12-1	=S4/T4	=U4/U6	=F.INV(1-Y$1,T4,T$6)	=(U4-U6)/G4	=IF(X4>0,X4,0)	=Y4/Y7*100
Interaction	=P6	=T3*T4	=S5/T5	=U5/U6	=F.INV(1-Y$1,T5,T$6)	=(U5-U6)/B4	=IF(X5>0,X5,0)	=Y5/Y7*100
Error	=P7	=T7-T3-T4-T5	=S6/T6			=U6	=U6	=Y6/Y7*100
	total DF	=G15-1				totals	=SUM(Y3:Y6)	=Y7/Y7*100

Fig. 1. Excel example results and code for Gauge R&R analysis.

ments of the resistors. They recorded the data in their Excel program. After that, the students checked for calculation errors. After all errors are corrected, they compared the calculated *F*-test statistics against the *F*-critical values for team, part, and interaction to find those that had significant variations. The contributions from team, part, interaction and error were used as indications for the relative amount of variations from each category.

Using the same test data, Gauge R&R analysis was conducted in Minitab. The results from Excel and Minitab were compared for consistency. If R&R was greater than 9%, students were supposed to identify the main source of the R&R variation. If it was mainly from the repeatability, then the measurement equipment was not acceptable. This could be due to a calibration problem or equipment malfunction. If the main variation was from the reproducibility, then there might be a problem with the teams properly using the equipment. Training for operators might be required to reduce the variation.

During the first semester of using the Gauge R&R learning module, an unexpected high level of reproducibility was found during the Gauge R&R analysis in one of the laboratory sections. Student teams used the raw data to try to find the root cause of the large reproducibility value. The regular Gauge R&R laboratory turned into a troubleshooting exercise.

Several student teams calculated the means and standard deviations in Excel for the measurements by parts and by teams. They quickly identified that the data from a specific team had a significant different mean value and a large standard deviation compared with other teams' data. This team repeated their measurements and found that their measurements were very inconsistent. A short brainstorming session was held to list all possible causes:

- a faulty multimeter;
- bad connection between the multimeter and the resistor; and
- operator error in using the multimeter.

A different digital multimeter was used, and the results were still inconsistent. Another team used the suspicious multimeter to measure resistance and got consistence and good results. Therefore, it was concluded that multimeter was not the cause. While the team with inconsistent test data was taking measurement, the instructor checked the setting of the multimeter and the way the team used the multimeter. Everything seemed to be done correctly. Next, the two leads from the multimeter were short-circuited to measure the resistance value. Instead of the expected 0 value, a large resistance value was displayed on the multimeter. This led to the inspection of the wires connecting the resistors and the multimeter. The resistance for one of the wire was found to be large and varying when the wire was jiggled. Cutting open the wire eventually revealed the root cause of the problem: the conduct inside the wire was broken. The two pieces of conducts were still in contact with each other, but the resistance could be a few hundred Ohms.

This unplanned troubleshooting success led to the additional laboratory step for the Gauge R&R analysis laboratory in the following semesters. A fault was inserted to the process and students were supposed to identify the root cause using Gauge R&R and other statistical analysis method. Specifically, the color code of the resistors was covered up in paper taped to the resistors so that the color code could not be seen. A resistor with different nominal value was mixed in the group of resistors that have the same nominal resistance. Using Gauge R&R analysis, students could always trace the problem to the "wrong" resistor.

Through this Gauge R&R laboratory exercise, students learned the concept of variation in measurements, Gauge R&R analysis using Excel and Minitab, and root cause analysis techniques, all of these are useful practical knowledge.

4. Evaluation of student learning

The instructor noticed that students were more actively involved in the Gauge R&R laboratory compared to other laboratory work. In the official student evaluation conducted at the end of the first semester, many students wrote positive comments about the root cause analysis experience during the Gauge R&R laboratory.

To carry out a quantitative analysis of student learning, students were asked to give themselves two evaluations on the knowledge of Gauge R&R among other things, one in the beginning and one at the end of the semester. Students rank themselves with a score of 1-10, with 1 representing "know nothing about this area" and 10 representing "an expert in the area". Over three semesters, 83 students submitted their self-evaluation forms. Student names were included in the survey forms so that the increase of the score for each student can be calculated. The raw data are given in Table 2 with the before and after scores from the same student recorded in the same column. One can see that the values for "After" are significantly higher than those of "Before" for most students.

The mean values, standard deviations, minimum values, maximum values, and ranges (defined as maximum–minimum) for "Before" and "After" self-evaluations were calculated in Table 3. The mean of "After" is much higher than "Before". The standard deviation also increased from "Before" to "After". The minimum of 1 for "After" was a surprise. Apparently, there were a few students who were frustrated by the concept and the lab exercise. The maximum value for "After" is much higher than that of "Before", which is what one would expect. As a result, the range for "After" is also larger than that of "Before". The low standard deviation for "Before" is an indication that students were consistently unfamiliar with the concept of Gauge R&R.

To further analyze the data, the differences between "After" and "Before" self-evaluations are calculated. The difference has an average of 4.819 and standard deviation of 1.945. Since the sample size of 83 is a reasonably large number, one can apply the Central Limit Theorem to claim that the average difference has a normal distribution. The 95% confidence interval for the difference between "After" and "Before" scores can be calculated with the following formula [55]

$$(\bar{X} - 1.96\frac{s}{\sqrt{n}}, \bar{X} + 1.96\frac{s}{\sqrt{n}}) \tag{30}$$

where $\bar{X}$ is the average of the differences, n is the

Table 2. Before and after comparison of student self-evaluation

Student #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Before	2	1	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
After	5	5	6	5	2	4	7	4	7	2	2	7	7	1	1	4	6	4	6	7	6
Student #	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Before	1	1	1	1	3	2	5	1	1	1	1	1	1	1	1	1	1	1	2	1	1
After	6	5	8	8	7	6	7	8	7	6	8	6	5	3	5	6	6	7	7	7	4
Student #	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
Before	1	1	1	1	1	1	1	1	1	2	1	1	3	1	1	1	1	1	2	1	1
After	5	7	6	7	7	7	4	5	7	5	1	4	7	6	3	7	8	8	9	8	7
Student #	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	
Before	1	1	1	1	1	2	1	1	2	1	1	1	1	2	1	1	1	3	1	3	
After	8	8	8	7	8	8	9	8	8	7	7	7	4	9	5	6	9	6	8	8	

Table 3. Statistics of collected data

	Mean	Standard deviation	Minimum	Maximum	Range
Before	1.28	0.7	1	5	4
After	6.1	1.9	1	9	8

sample size, and s is the standard deviation of the differences. Using the raw data, the 95% confidence interval for average difference is calculated to be (4.401, 5.237). This means that the students believed that they have made significant improvement in Gauge R&R during the course.

5. Discussion

Instead of just teaching the Gauge R&R theory in a lecture, four categories of learning defined in the Bloom's Taxonomy of student learning: remembering, understanding, applying, and analyzing, were involved in the learning modules presented in this paper. The laboratory exercise was designed based on a well-known conclusion that engineering technology students learn better with hands-on experience. Through hands-on experiential learning, students remember and understand the concept better. By applying Gauge R&R to solve a problem, the applying and analyzing categories are involved in student learning. These higher level learning activities can significantly enhance students' learning of Gauge R&R.

Using Gauge R&R as a problem solving tool is a unique way to teach Gauge R&R. While it is possible to deploy similar educational modules to other engineering and engineering technology majors, the design of the problem requires some creativity for each major.

The main objective of this paper is to disseminate the experience gained and lessons learned in ESET 329 to the community of engineering educators. Through the limited amount of assessment effort, the preliminary results seem promising. The student self-evaluations, which were done before and after the learning module was delivered, provide a quick way to gather assessment data. It only reflects the opinion of the students. As more applications of this approach occur in higher education institutions, more rigorous studies on student learning may be conducted. For example, if conditions allow, two laboratory sections can be selected with one control group and one experimental group. The Gauge R&R theory can be taught in the class where both groups attend. The experimental group would go through the root cause analysis exercise using Gauge R&R. An exam problem related to Gauge R&R would be given to both groups. The test results would be analyzed to see if there is a significant difference in student learning. This would provide a more objective evaluation in complement to the student self-evaluations. However, the assessment through analyzing the student performance in exam problems has its potential problem as well. There is always randomness involved in a timed examination when students are under pressure. A solution to this problem is to increase the sample size. This can be achieved by repeating the assessment in multiple semesters.

Some students may learn about the problem and the root cause beforehand from other student who took the course earlier. Therefore, it is also desirable to have multiple problems that can be used in different semesters.

6. Conclusions and future work

A module with lecture, laboratory testing, and data analysis components for learning GR&R was developed for a course "Applied Statistics and Six Sigma" offered to the electronics system engineering technology students. Students learned the theory of Gauge R&R in a lecture first. They wrote an Excel program for Gauge R&R analysis. This program was then used to analyze the test data they collected. The same analysis was conducted in Minitab to confirm the result from their Excel program. An unplanned fault and an inserted fault were identified by the students using the Excel program they developed. Based on the student self-evaluations, this hands-on experiential learning worked well for engineering technology students.

Future research work will be conducted to enhance the learning module. The improvement of student learning will be monitored by collecting more data. Additional surveys will be designed to get more detailed information about the effectiveness of the methodology being used to teach Gauge R&R. In addition to the faulty resistor being mixed up with the normal resistors, other fault-insertion methods are being considered for the root cause analysis laboratory exercise. It is also proposed that Gauge R&R be used in other courses after ESET 329 to reinforce the knowledge the students learned.

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