Introducing ChE Sophomores to Measurement System Analysis and Analysis of Variance through Experiential Learning

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Abstract
Measurement System Analysis provides a formal method to evaluate the accuracy and precision of a measurement gauge. Although it is an important topic, it is typically omitted in introductory statistics classes, and often only receives cursory coverage in lab. This paper describes how this topic is introduced through experiential learning to ChE sophomores at Oregon State University (OSU). The introductory concepts are presented in class where a "text book" example allows students to learn how to decompose the variance components of a measurement gauge. In a homework assignment, students are asked to work through a case study from industry. This analysis leads to the quantification of the gauge's precision in terms of repeatability and reproducibility. They are then asked to perform a similar analysis on measurements that they take in the lab from a different gauge. In this lab, they make a series of thickness measurements of silicon dioxide films using an ellipsometer; however, in principle, this approach can be applied to any measurement system available in the undergraduate lab. In their report, they are required to calculate the repeatability and reproducibility of the gauge "by hand" in Excel. The experimental results and calculations are assessed by the instructor with output from commercial statistics software package, StatGraphics; thus, the accuracy of the numerical results of each group can be checked even though they all have independent data sets. In Spring 2004, 49 students completed this case study/lab project.

Introduction
As educators are well aware, the customary educational setting in which students develop problem solving skills is one where the numerical values presented are specific and absolute. The deterministic nature of the end-of-chapter type problems is imbedded in their minds well before students even matriculate. However, as practicing engineers, they will confront the variation associated with measured data in the real world. Statistics can be defined as the science of how to collect, analyze, interpret and present data with the purpose of understanding variation in a system. A key objective of integrating statistics into the ChE curriculum is to have students recognize variation is inevitable, and teach them skills to quantify the variation and make engineering decisions which account for it. Indeed, the importance of statistics is well recognized

in the chemical engineering community. For example, several recent articles in *Chemical Engineering Progress* have focused on applied statistics.[1-5] Many chemical engineering programs have incorporated statistics into their curriculum.[6] Several ChE specific courses in applied statistics have been recently reported.[7-10] The example presented here provides a hands-on example of how to quantify the variation associated with a measurement gauge. This material can either be integrated directly into an introductory statistics class or, alternatively, taught as a "module" in a core ChE class, as is done at Oregon State University.

Experimental or process data are obtained through a measurement system. Values of variables such as temperature, pressure, flow rate, concentration, thickness, etc. are needed to analyze and control processes. If we are not able to adequately make measurements, we cannot hope to make useful decisions. The first step in assessing and analyzing data should be to characterize the measurement system. Measurement System Analysis evaluates the measurement instruments in order to determine their accuracy and estimate the sources of variation and their extent. The process of evaluating a particular set of measurement instruments is often called a gauge study. For example, a gauge study is the first step in the formal process and equipment qualification plan developed by SEMATECH, a government supported consortium of major US semiconductor manufacturers.[11,12] In fact, many interns and recent college graduates are tasked with executing gauge studies. However, most engineering statistics textbooks either omit this topic[13-21] or, at best, cover it in a cursory manner.[22] This paper describes how this topic is introduced to ChE sophomores through experiential learning. The introductory concepts are presented in class where a "text book" example allows students to learn how to decompose the variance components of a measurement gauge. In a homework assignment, students are asked to work through a case study from industry, which is then reviewed in class. They are then asked to perform a similar analysis on measurements that they take in the lab from a different gauge. This topic not only gives process engineers a useful tool for immediate practice but also provides a useful platform to learn about variation and variance.

Measurement System Analysis

The major concepts of measurement system analysis are first introduced in a class handout.[a] A measurement process is the acquisition of data in a specified way using a gauge or measuring instrument. The objective of a gauge study is to characterize the location (central tendency) and variability (dispersion) of the measurements. From this information, we can determine if the measurement system is capable for the purpose for which we need the data.

Concepts of accuracy, calibration, bias, stability and linearity are introduced to characterize the location of the measurements. The accuracy of a measurement process is the difference between the observed average of the measurements and the true value. The true value is determined from a standard, if available, or it can be approximated by measuring with the best measuring equipment available. The observed average is determined by a series of measurements with the measurement system in question. Bias is defined as the difference between the average value of all measurements and the true value. Thus, the less bias a gauge exhibits, the more accurate it is.

[a] Contact the author if you want a copy of the handout, examples and homework problems.

A measurement device (gauge) can be calibrated to reduce bias. Stability is a measure of how consistent the measured values are over time.
The variation in the measurement system is characterized by its precision. Precision is the degree of agreement between measurements on a specific sample. It consists of variation from two sources: repeatability and reproducibility.

Precision = Repeatability + Reproducibility

These components are illustrated graphically in terms of a characteristic normal distribution in Figure 1. The repeatability is the variation of measurements when a single instrument is used to measure a sample under a fixed set of external conditions. It represents the inherent variability of the measurement instrument, itself. The reproducibility is the variation in the measurements due to different conditions when measuring identical samples such as different operators, environments, or measuring instruments. It represents the variability that results from using the measurement system to make measurements under different conditions of normal use. The learning activities that follow (case study and lab) illustrate how to account for the variability in a measurement system. From the results, it can be assessed if the measurement system is capable. If it is not capable, this analysis allows one to determine if the variability is inherent in the gauge or if there is an opportunity to improve the measurement process without replacing the gauge.

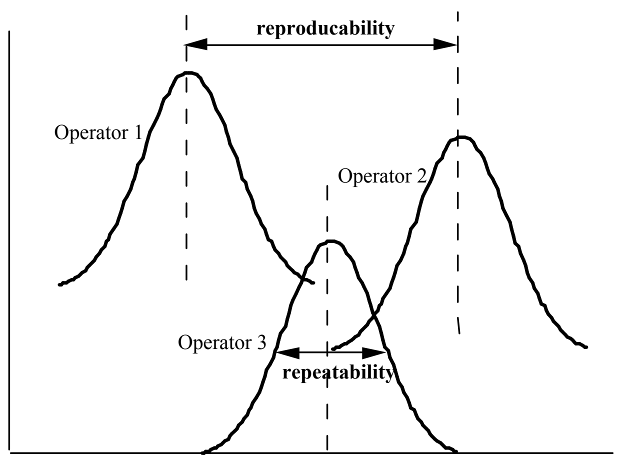

Figure 1. Components of precision including reproducibility and repeatability

Gauge R&R Case Study
The case study introduced is based on data collected by an OSU ChE interning at Merix Corporation, a printed circuit board manufacturer in Forest Grove, OR.[b] This study was performed to evaluate the capability of a video micrometer in use and assess if newer instruments needed to be purchased. While the experimental design is an important component to this process, that methodology is not covered and the design that was used is simply presented.

[b] While the data from Merix were used, the analysis that follows differs significantly.

Three different samples, n, are measured by four different operators, m. Each operator performed three repeated readings, k on each sample. The samples were taken at random from production. The operators and samples are treated as random factors (as opposed to fixed factors), i.e., the factor levels that are specifically used in the experiment are chosen at random from a larger population of levels. Table 1 shows the measured values in mils (1 mil = 25 µm) of the line width of metal lines on a printed circuit board. Since many students are visual learners, it is useful to represent the data and their sources of variation graphically. Figure 2 shows a depiction of the 36 values of line width from this gauge study. This particular study was chosen in part since the sample size is amenable to such a graphical representation. The values of measured line width are given on the *x*-axis. The nine values of operator Brad data are shown on the top third of the figure, Operators Jon, Tim and Edger follow. The three values obtained by each operator for each sample are presented in order, followed by the next sample, and the third. The scatter in the data relative to the *x*-axis is an indication of the variance in the measurement system.

Table 1. Measured values of line width (in mils) for the video micrometer gauge study

Operator: Brad

Sample	Reading	Measurement
	1	5.08
1	2	5.16
	3	4.94
	1	6.16
2	2	5.84
	3	5.82
	1	6.01
3	2	5.99
	3	6.00

Operator: Jon

Sample	Reading	Measurement
	1	5.08
1	2	4.98
	3	4.98
	1	5.55
2	2	5.53
	3	5.62
	1	6.03
3	2	5.89
	3	5.94

Operator: Tim

Sample	Reading	Measurement
	1	5.21
1	2	5.01
	3	5.12
	1	5.91
2	2	6.09
	3	6.06
	1	6.02
3	2	6.08
	3	5.95

Operator: Edgar

Sample	Reading	Measurement
	1	4.98
1	2	5.01
	3	4.99
	1	5.63
2	2	5.84
	3	5.85
	1	5.90
3	2	5.96
	3	5.95

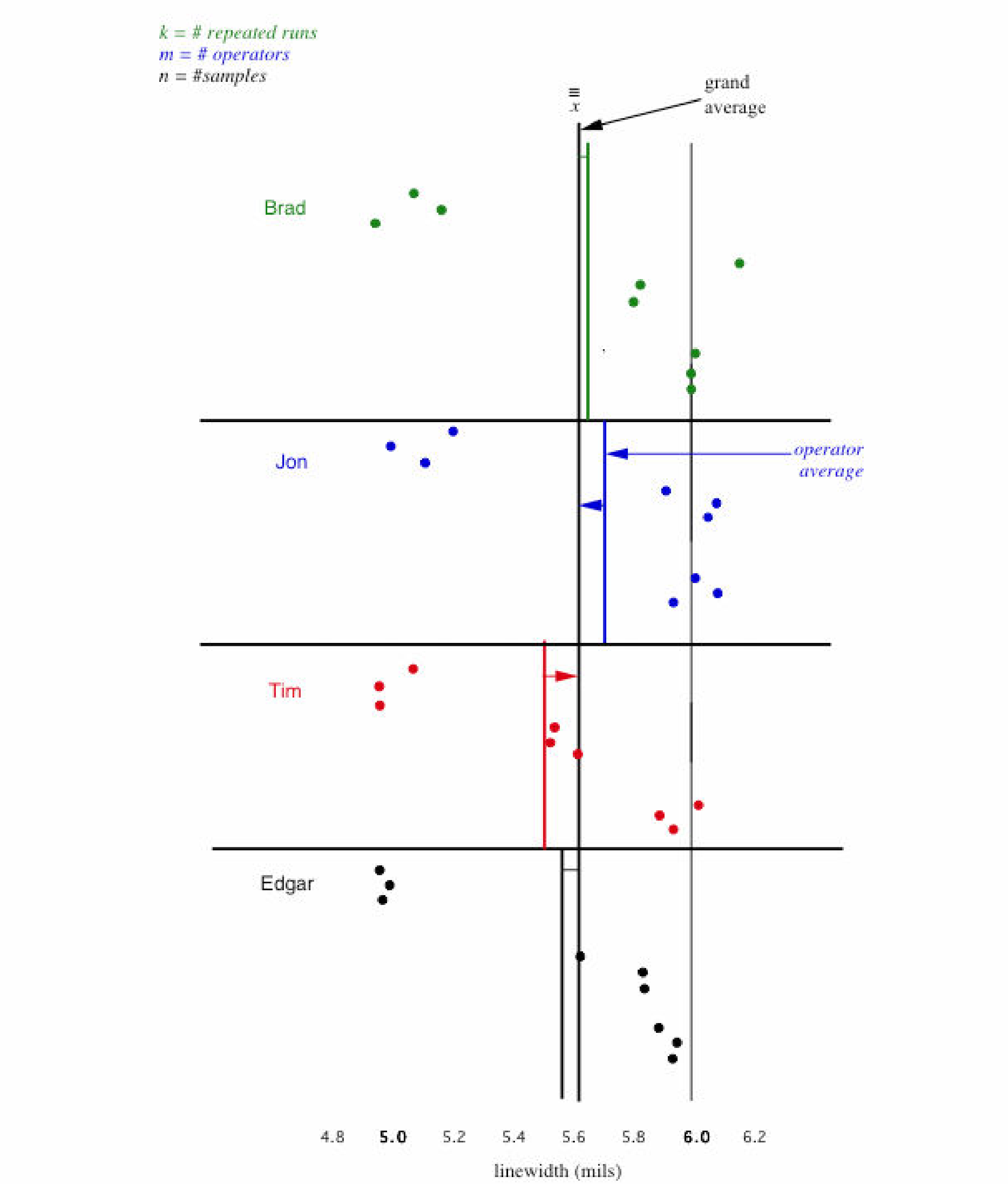

Figure 2. Graphical representation of data from the case study.

The quantification of the precision and its reduction into components of repeatability and reproducibility is based on the variation in the measured data. Through the technique of analysis of variance (ANOVA), we can decompose the total variation of the system into components corresponding to different sources of variation.[23] We develop the concept of variance components heuristically in analogy to definitions of standard deviation and variance, which are already known. In fact, this approach has elements of inductive learning, where students learn the generalized theory from specific examples that they have investigated closely.[24] In the following analysis, these calculations are illustrated using the data from Table 1.

Repeatability measures the variability inherent in the micrometer, itself, when all the external conditions of the measurement process are identical. To determine the repeatability, we compare the deviation of each measured value from the average of all the repeated measurements from the same sample, *n*, and the same operator, *m*, which is labeled $\bar{x}_{mn}$. It is useful to have students draw in lines that demark $\bar{x}_{mn}$ for each of the 12 cases in Figure 2. We can see that the deviation of a repeated reading from its average, with all conditions being the same, is given by $(x_{kmn} - \bar{x}_{mn})$, where *k* is the number of the repeated measurement. The variance from each point is then the square of the deviation, $(x_{kmn} - \bar{x}_{mn})^2$. The total variation due to this component is given by the sum of the squares, $SS_{repeated}$, by summing over all 36 data points:

$$SS_{repeated} = \sum_{k,m,n} (x_{kmn} - \bar{x}_{mn})^2 = 0.200 \left[\text{mil}^2\right] \quad (1)$$

The expression above uses a triple sum over repeated readings, operators and samples. The numerical value that is given in Equation 1 corresponds to the data from Table 1. The calculations are performed in a computer-enhanced class by the students using a spreadsheet so they can "see" where the numbers come from. We next need to scale this value appropriately. Thus, we divide $SS_{repeated}$ by the degrees of freedom to get the mean squares of the repeated measurements, $MS_{repeated}$. The degrees of freedom is equal to the number of independent elements in $SS_{repeated}$. Once we know the average $\bar{x}_{mn}$, only *k-1* elements are independent for each pair of *n* and *m*. Thus, the degrees of freedom are given by *nm(k-1)* and the mean squares is:

$$MS_{repeated} = \frac{SS_{repeated}}{nm(k-1)} = 0.00831 \left[\text{mil}^2\right] \quad (2)$$

The expected value of the population standard deviation, σ, is defined as:

$$E(MS_{repeated}) = \sigma^2_{repeated} \quad (3)$$

The **reproducibility**, in this gauge study is characterized by the variance in values due to differences in the measurement process, in this case between operators. Reproducibility can also be assigned to different environments, different gauges, etc. Only one external source of variation is examined in this study; however, for completeness as many sources of variation as possible that influence the measured values should be included. This variance component can also be understood in terms of the graph in Figure 2. It is given as the difference between the grand average $\overline{\overline{\overline{x}}}$ and the average of all measurements by a given operator $\overline{\overline{x}}_m$. The variance component that is used to calculate the reproducibility is demarked by colored arrows; for example a blue arrow is used for the operator John. Summing over all four operators gives:

$$SS_{Operator} = \sum_{k,m,n} \left(\overline{\overline{\overline{x}}} - \overline{\overline{x}}_m\right)^2 = kn \sum_{m} \left(\overline{\overline{\overline{x}}} - \overline{\overline{x}}_m\right)^2 = 0.234 \left[\text{mil}^2\right] \tag{4}$$

where the value k and n can be pulled outside the sum since they are averaged in both terms. Again the mean sum of the squares is found by dividing by the degrees of freedom to get:

$$MS_{Operator} = \frac{SS_{Operator}}{(m-1)} = 0.0781 \left[\text{mil}^2\right] \tag{5}$$

There is another effect that the operators contribute to the variation, given by the *interaction* between operators and samples.[23,25] The interaction results from systematic differences between operators as they measure different samples. For example, if one operator consistently got smaller values than another when measuring thin lines but larger values when measuring thick lines. The interaction between operators and samples can be calculated:

$$SS_{Interaction} = k \sum_{m,n} \left(\overline{\overline{\overline{x}}} - \overline{\overline{x}}_m - \overline{\overline{x}}_n + \overline{x}_{mn}\right)^2 = 0.166 \left[\text{mil}^2\right] \tag{6}$$

Again the mean sum of the squares is found by dividing by the degrees of freedom to get:

$$MS_{Interaction} = \frac{SS_{Interaction}}{(m-1)(n-1)} = 0.0277 \left[\text{mil}^2\right] \tag{7}$$

The expected mean squares of the interaction is given by contributions from both the repeatability and the interaction:

$$E(MS_{Interaction}) = \sigma^2_{repeated} + k\sigma^2_{Interaction} \tag{8}$$

Hence

$$s^2_{Interaction} = \frac{MS_{Interaction} - s^2_{repeatability}}{k} = 0.00647 \left[\text{mil}^2\right] \tag{9}$$

Similarly, the expected mean squares of the operators is given by contributions from the repeatability, the interaction and the operators:

$$E(MS_{Operator}) = \sigma^2_{repeated} + k\sigma^2_{Interaction} + kn\sigma^2_{Operator} \qquad (10)$$

Hence

$$s^2_{Operator} = \frac{MS_{Operator} - ks^2_{Interaction} - s^2_{repeatability}}{kn} = 0.0056\left[\text{mil}^2\right] \qquad (11)$$

The sample standard deviation due to repeatability, $s_{repeated}$, which estimates the corresponding population standard deviation can be found by Equations 2 and 3:

$$s_{repeated} = \sqrt{MS_{repeated}} = 0.0912\left[\text{mil}\right] \qquad (12)$$

Similarly, the sample standard deviation due to reproducibility (different conditions) is found according to contributions from both the Operators and interactions:

$$s_{reproduc} \approx \sqrt{s^2_{Operator} + s^2_{Interaction}} = 0.110\left[\text{mil}\right] \qquad (13)$$

The precision, $s_{r\&R}$, is estimated by adding together the contribution from both of these components:

$$s_{r\&R} = \sqrt{s^2_{repeated} + s^2_{reproduc}} = 0.143\left[\text{mil}\right] \qquad (14)$$

For this case study, 41% of the variation is estimated to be due to repeatability and 59% to reproducibility. There is a significant contribution from each source of variation. This result indicates improvement to the measurement system could be made by improving the measurement process of the operators, but if substantial improvement is needed a new measurement system would be needed. In other cases, this type of analysis can tell the engineer the inherent variability of the gauge is the dominant source of variation, or, conversely, that the measurement process, is responsible for most of the variation in the measurement and the gauge, itself, is capable.

The precision to tolerance ratio (*P/T*) is used to assess the capability of a gauge to give satisfactory measurements. It is given by:

$$\frac{P}{T} = \frac{6s_{r\&R}}{USL - LSL} \qquad (15)$$

where *USL* and *LSL* are the upper and lower specification limits of the process, respectively. A small precision to tolerance ratio is desirable so that only a small portion of the tolerance is consumed by measurement variability. Values of P/T less than 0.3 are considered acceptable; values less than 0.1 are good.

It is illustrative to look at the variation in the samples as well. In analogy to the development above, the variation in the samples can be described by the sum of the squares of the samples, SS_{sample}. In this case, the variance is represented by the difference between the sample average, $\bar{\bar{x}}_n$, and the grand average, $\bar{\bar{\bar{x}}}$, which averages over all 36 measured values in the study. This component of variation is given by:

$$SS_{sample} = \sum_{k,m,n} \left(\bar{\bar{x}}_n - \bar{\bar{\bar{x}}}\right)^2 = km \sum_{n} \left(\bar{\bar{x}}_n - \bar{\bar{\bar{x}}}\right)^2 = 6.00 \left[\text{mil}^2\right] \qquad (16)$$

Again the values k and m are brought outside the sum since each term is averaged over the repeated readings k and the operators m. The mean squares is given by dividing SS_{sample} by the degrees of freedom:

$$MS_{sample} = \frac{SS_{sample}}{(n-1)} = 3.00 \left[\text{mil}^2\right] \qquad (17)$$

Finally, the estimate of the standard deviation from the sample is given by

$$s_{sample} \approx \sqrt{\frac{MS_{sample} - MS_{operator}}{km}} = 0.496 \left[\text{mil}\right] \qquad (18)$$

As an alternative to P/T ratio can use:

$$\frac{s_{R\&R}}{s_{sample}} = 0.33 \qquad (19)$$

This result allows us to assess the capability of the gauge in examining variation in the system irrespective of the specification limits. In this case, the standard deviation due to the measurement system is 33% that of the sample.

The total sum of the squares is found from the deviation of each measurement from the grand mean of all the measurements:

$$SS_{total} = \sum_{k,m,n} \left(x_{kmn} - \bar{\bar{\bar{x}}}\right)^2 = 6.60 \left[\text{mil}^2\right] \qquad (20)$$

The resulting standard deviation is that which students are accustomed to seeing:

$$s \approx \sqrt{\frac{SS_{total}}{kmn-1}} = 0.434 \left[\text{mil}\right] \qquad (21)$$

Alternatively we can find the total sum of the squares by adding together the three components described above:

$$SS_{total} = SS_{sample} + SS_{operator} + SS_{Interaction} + SS_{repeated} \qquad (22)$$

Equations 20 and 22 yield identical results. Finally these results can be summarized in an "ANOVA Table," as illustrated in Table 2.

Table 2. ANOVA Table for the gauge r&R case study

	Sum of the Squares (SS)	Degrees of Freedom (ν)	Mean Sum of the Squares (MS=SS/ν)	F-Ratio $=MS_i/MS_R$	p
Samples	$SS_S = km\sum_{n}\left(\bar{\bar{\bar{x}}} - \bar{\bar{x}}_n\right)^2 = 6.00$	$n - 1 = 2$	3.00	360.	0.0000
Operators	$SS_O = kn\sum_{m}\left(\bar{\bar{\bar{x}}} - \bar{\bar{x}}_m\right)^2 = 0.234$	$m - 1 = 3$	0.0781	9.39	0.0003
Interaction = Operators x Sites	$SS_{Int} = k\sum_{m,n}\left(\bar{x}_{mn} - \bar{\bar{x}}_m - \bar{\bar{x}}_n + \bar{\bar{\bar{x}}}\right)^2 = 0.166$	$(m-1)$ x $(n-1) = 6$	0.0277	3.33	0.0153
Repeatability (Error)	$SS_R = \sum_{k,m,n}\left(\bar{x}_{mn} - x_{kmn}\right)^2 = 0.200$	$mn(k-1)=24$	0.0083		
Total	$SS_{Total} = \sum_{k,m,n}\left(\bar{\bar{\bar{x}}} - x_{kmn}\right)^2 = 6.60$	$kmn - 1 = 35$			

Gauge R&R Lab Study

Students were then given a "hands-on" opportunity to apply what they had learned in class and in the case study and perform a Gauge R&R study in the lab. In this experiment, they measured the thickness of SiO_2 films on 6"silicon wafers using ellipsometry. This process was selected since measurements can be made rapidly and it gives them experience with an important measurement system used in the microelectronics industry. In principle, any measurement system available in the undergraduate lab that allows students to get the necessary data within the time allotted for the lab can be used. Groups of three or four students were used so that they could measure the operator variation (reproducibility) in addition to the repeatability.

Ellipsometry measures the change in polarization of light reflected off of a surface. This process together with the experimental system used in the lab is shown in Figure 3. In ellipsometry, a wafer is placed on the sample table. The ellipsometer emits monochromatic, polarized light. Some of the light reflects off of the thin film surface and some of it reflects off of the substrate surface. The change in polarization is measured by the detector. The polarization change can be

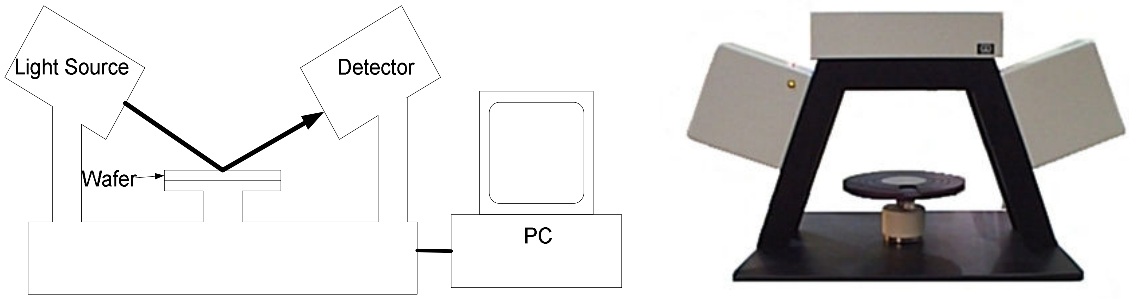

Figure 3: Ellipsometry measurement gauge for film thickness.

used to determine the change in phase and the change in amplitude of the light. Given the index of refraction and an initial guess of thickness, the thickness of a film can be determined.

In this experiment, each student "Operator" (***m* = 3 or 4)** measures the thickness of three Sites (***S* = 3)** (1=center, 2=half way in between, 3=close to edge) on two Wafers, (***W* = 2**). The each perform two repeated runs (***k* = 2).** Thus each student makes 12 measurements and each group has 36 or 48 data points to analyze. A design array used to collect the measured data for a group of three students is shown in Table 3. The students were given a sample set of three wafers from which they were to use two. Two were close in thickness while the third differed.

Table 3. Design array used for the gauge study in the lab

W	***S***	***O***	T (*k*=1)	T (*k*=2)
1	1	1		
1	2	1		
1	3	1		
2	1	1		
2	2	1		
2	3	1		
1	1	2		
1	2	2		
1	3	2		
2	1	2		
2	2	2		
2	3	2		
1	1	3		
1	2	3		
1	3	3		
2	1	3		
2	2	3		
2	3	3		

In their report, students were asked to (i) calculate the mean, variance and standard deviation of all measured data; (ii) perform a gauge study for Wafer 1 reporting the repeatability and reproducibility values: $s^2_{repeatability}, s^2_{reproducability}, s^2_{r\&r}$, $s_{repeatability}, s_{reproducability}, s_{r\&r}$, % repeatability , % reproducibility. (iii) repeat for Wafer 2; and (iv) An ANOVA analysis on the sample, not including interactions, i.e., the variance components from wafer, site and operators. They were also asked how do the r&R values for wafer 1 and wafer 2 compared and if they made sense.

Commercial Statistics Software and Assessment of Student Performance
In practice, statistical analysis is usually performed with software, using either a dedicated software package or the statistical add-ins associated with a spreadsheet package. There are many common statistics programs used including: Minitab, StatGraphics, Statistical Applications System – JMP, and Statistica. The experimental results and calculations are assessed by the instructor with output from commercial statistics software package, StatGraphics; thus, the accuracy of the numerical results of each group can be checked even though they all have independent data sets. To facilitate this process, students were asked to submit their results electronically, in Excel files which were formatted to directly import to StatGraphics. Only six of the fifteen groups had calculations correct. The next time this module is used, a greater emphasis will be placed on numerical accuracy. Once the reports were turned in, students were shown how to use the computer program to perform these calculations. The exposure to statistics software is not intended to train the students on a particular software package but rather to get them to integrate the concepts developed in this exercise to intelligently use statistics software. The premise is that if students can apply the core concepts that they have learned to a particular software package, it will be straightforward for them to apply it to any other package as well.

The learning objective for this activity is listed in the syllabus as follows: “The student will demonstrate the ability to: design, implement, and analyze experiments to measure the repeatability and reproducibility of a gauge; perform ANOVA analysis to estimate the variance components from different sources.” In addition to the homework and lab project, two assessments were used to measure the learning outcomes from this exercise. Students were given a quiz in class. The average score was 79%. This compares to 82% for the other quizzes in the class, which covered non statistics-based topics. Thus, the numerical score was roughly equivalent. The quiz scores were also categorized by those students who had taken an introductory statistics class and those who had not, with scores of 83% and 75%, respectively. Additionally, measurement system analysis was previously taught as part of a dedicated statistics class (no longer offered). In that course, while the case study was used, but the lab was not. In three years, one problem on the midterm exam addressed measurement system analysis. Scores were 63%, 69% and 82%. While this may indicate that the lab component is useful, the nature of the questions on the exams and the context in which the material was presented was different. Thus, the no lab may have limited value as a control case. The students were also asked to perform a self-assessment of how well they achieved this learning objective.

Summary
A key component to quality improvement strategies is to understand the variation in a chemical process. The data used to assess the variation is obtained through measurement tools. Measurement system analysis can quantify the contribution of the complete measurement process to the overall variation in the process. These methods are often used by practicing engineers and are appropriate to teach in the chemical engineering curriculum. This paper illustrated a gauge r&R study through a case study taken from industry and then application in the lab. This scope of this study allows the data to be plotted graphically and the variance components to be induced from the graphical approach, leading to a methodical account of different sources of variation. The details of calculating the precision of a measurement gauge can then be taught. Measurement system analysis is an excellent topic for integration into lab courses. The design presented in class is then applied in the lab. The use of StatGraphics software allows each group's results to be checked for numerical accuracy.

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