A STUDY OF HUMAN MEASUREMENT ERROR
IN A CONTROLLED EXPERIMENT FOR
MICROMETER MEASUREMENTS

by

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CHAPTER I

INTRODUCTION

Initial Comments

This is an exploratory thesis. The objective of this thesis is to isolate human measurement error in a physical measuring environment. A secondary objective is to evaluate this measurement error, if successfully isolated, with respect to its effect of biasing statistical quality control tests that describe a manufacturing process.

The author of this report designed a specialized measurement jig that was used to isolate human measurement error. Specifically, the tests involved seven human inspectors making micrometer measurements of the diameters of cylindrical brass pieces. Several physical factors were rigidly held in control or eliminated by the design of the jig and the experimental process. This was necessary to obtain as accurate an estimate as possible of the human error.

The human measurement error in this experiment was successfully isolated. Further analysis of this measurement error led to the hypothesis that it probably can bias statistical quality control tests that describe a manufacturing process. This bias is reasoned to have a greater effect on statistics that describe processes with very close physical tolerances.

The General Concept

Today there is very little, if any, resistance from manufacturing engineers that every manufacturing process produces a product with inherent variabilities. It is from this base that quality control engineers are attempting to determine what factors of a manufacturing process contribute to this variability, which ones are controllable, which ones are not, and which ones are predictable. Although several variables affecting a manufacturing process have been rigorously defined and generally understood, there are still variables that are only suspects, and their real contribution to process variation is unknown.

Dr. Roger L. Smith, while functioning as Professor of Industrial Engineering, Virginia Polytechnic Institute, developed the concept that the variability of any manufacturing process, developed into a workable and reliable state, can be considered influenced by the following factors:

1. the machine,
2. the magnitude of the dimension of the product,
3. the material,
4. the operator, and
5. the specification tolerances.

Research on this specific concept has further developed that the following three factors offer little or no contribution to process variability:

1. the machine, if lathes are compared to lathes, grinding machines are compared to grinding machines, etc., and that the machines

are in proper working condition,

2. the operator, but only if the operator is experienced and competent, and

3. the magnitude of the dimension, but only within some specified ranges (3,5,6).

These results indicate that the only factors significantly affecting the process variation are:

1. the material, and

2. the specification tolerances.

However, one of the suspected variables is not included in the above list and is external to the process variations. It could drastically change the environment of quality control if found to be significant. This suspected variable is the human error of measurement in the procedures of establishing whether or not a process is out of control. This variable is the objective of this research. Although this measurement error does not directly affect the variability of a manufacturing process, it could directly affect the statistical descriptions of the estimates of the process variability. In many production environments, periodic samples are taken from the output product of a manufacturing process, physical measurements are made by human inspectors, and the results tabulated and compared against statistical quality control standards established to indicate the acceptable variability of the product. If the errors introduced by the physical measurements significantly biased the sampling results, the process could appear out of control when in fact it was not, or vice versa. Techniques would be needed to eliminate this human variability from the sampling results. In other words, some technique of prediction of a humanly introduced error would be necessary to allow sampling techniques to clearly show the real process variation. The statistical tests estimate the process variation. This estimation, or apparent process variation, is made up of the true process variation and the human measurement error.

It goes without elaboration to state that human beings make errors, both mentally and physically. It is known and accepted that quality control inspectors do make mistakes in taking physical measurements to evaluate manufacturing process variabilities. However, quality control engineers have generally assumed that these inspector measurement errors do not significantly alter the results of the statistical sampling tests which describe the inherent process variability. In other words, the calculated process variation biased by human measurement errors is not felt to be significantly different from the true process variation. A general assumption clearly must be that the inspectors making these errors are experienced and competent measurers who hold their errors to a minimum, both in quantity and magnitude.

In the strict theories of measurement, the actual or true dimension, weight, etc. of any physical thing can never be found. Even the most elaborate electronic measuring devices today do not give the true measurement that is sought. However, an elaborate measuring device will give a measurement which is closer to the real dimension than will a simple measuring device. This ability to approach the true dimension is defined as the accuracy of measurement. A quality control inspector who uses a micrometer cannot be expected to find this true dimension he is measuring. How consistent this inspector is in making repeated measurements is a significant factor. In effect, the process of the inspector taking repeated measurements of a product sample is analogous to a manufacturing process. The inspector creates variability in his measurements, a consistent error in a sense, much like a manufacturing process creates variability in its products. This inspector measurement variability is defined as precision. A more precise inspector would be one who has more consistency, or less variability, in repeated measurements of the same true dimension.

Purpose

The purpose of this experiment is to design a technique by which human error in measurement can be isolated from the process variation.

The area of study will involve seven human inspectors using a micrometer to measure the diameter of brass pieces. The total group of brass pieces are made up of two populations of different sizes, 1/2 inch and 5/8 inch diameters.

When isolated, the significance of the measurement error will be evaluated with respect to its contribution to the apparent variation of the process that produced the parts that were measured.

Objective

The objective of this experiment is to isolate human measurement error within the confinement of the experiment. The secondary objective of this experiment is to determine whether or not human error in measurement significantly affects the apparent variation of the pieces being measured. The significance of this error will be evaluated in terms of:

1. experienced versus inexperienced inspectors, and
2. the size of the dimension measured in the range of .500 inches to .625 inches.

Results

This experiment is successful in isolating the human measurement error. Each of the seven inspectors used in this experiment is shown to have a unique measurement error for each of the two sized pieces measured.

The estimate of the measurement error is removed from the apparent process variation, the between sample variation biased by the measurement error. The remaining variation is an estimate of the true process variation, an unbiased estimate of the process variation.

Statistical tests on the measurement error estimates show that three of the seven active participants have different measurement errors for the two different sized pieces. Two show greater measurement errors for the 5/8 inch pieces. One shows a greater measurement error for the 1/2 inch pieces.

Statistical tests on experienced versus inexperienced measurers show that the experienced measurers are significantly more precise than the inexperienced measurers for the 1/2 inch pieces. Similar tests for the 5/8 inch pieces show the two groups to have measurement errors that are not significantly different.

The author sets an arbitrary standard that measurement error is significant when its estimate equals or exceeds the estimate of the true process variation. Based on this standard, eight of the fourteen individual experiments of this research project gave estimates of measurement error that equaled or exceeded the estimates of the true process variation.

One isolated incident of poor accuracy on the part of one inspector in this experiment showed evidence that poor accuracy can result in a false description of the true process variation. Although this point was not an objective of this research, its appearance does show that accuracy of measurement can also bias statistics that describe a process variation. This bias appears in a fashion quite different from the fashion that the precision bias appears.

Statistical tests further show that changes in a process variation do not create significant changes in measurement errors. These results lead to the hypothesis that measurement errors, appearing to remain constant for an individual, become more significant toward biasing statistics that describe a process variation when the true process variation decreases.

Related Studies

Published literature relating to human measurement error is very sparce. In most cases, each report deals with an unique or specific situation. With the exception of Steckler (6), none of the published literature found in a search of the literature deals directly with trying to isolate the human measurement error and further to analyze its contribution to the process variation. Actually, Steckler used the author's experimental apparatus as a side experiment to his research. He merely wished to substantiate that an industrial inspector in his experiment was fairly consistent with his measurements. He was not particularly concerned with the inspector's measurement error biasing the sampling statistics.

Two published articles, (1) and (2), deal with industrial inspectors and their human fallibility. However, they do not address themselves to the contribution of the error to the statistical description of the process producing the parts being tested.

The only other article the author found that appeared to approach his research topic was (7). However, this paper was strictly addressed to a "yes-no" visual inspection environment.

CHAPTER II

PRACTICAL EFFECT OF THE CONCEPT

Acceptance Sampling

In the process of acceptance sampling, the statistical results of the sampling data dictate whether or not the entire product job lot does or does not meet standard specifications. If the specifications are not met, then the entire lot is rejected. Even with a possible salvage value, the cost of production and loss of anticipated profit of this rejected product job lot creates a significant reduction in the profit picture for the company.

In the situation where the tested tolerance specification of a product is a physical dimension which is measured by a human inspector, the accuracy and precision of the inspector's measurements could affect significantly the statistical results of the sampling tests. The effect becomes significant if the measurement errors bias the estimated process variation by an amount to show the process to be out of control when in fact it is in control, or vice-versa.

Few would argue the point that given a very poor inspector whose precision and/or accuracy was extremely beyond some generally accepted standard then his readings could create statistical results clearly indicating the product job lot to be outside the design specifications. But within industry this type of individual should not exist, and hopefully would be discovered very quickly and removed from the job. In real life, this inspector will have received sufficient training and supervision on how to do his job as correctly and carefully as possible. The truly significant effect then would have to be reduced down to the amount of measurement error introduced by a qualified inspector's precision and/or accuracy in measuring. This amount of measurement error does contribute toward biasing the statistical description of the apparent process variation.

If it could be proven that in general measurement error causes the estimate of process variation to appear to be beyond the design limits when in fact the true process variation is within these limits, then precautions could be taken to anticipate this error. Some method could be devised to separate this specific variation introduced by the measurement errors from the apparent or estimated process variation to find the true process variation in the sampling procedures. Then the possibilities of discarding good product lots shown to be bad by humanly biased statistics would be reduced if not eliminated. The monetary rewards of such a development could be very significant.

This discussion of statistics biased by this human measurement error describing a good process to be out of control, or vice-versa, should not be confused with the type I and type II errors of statistical tests. The type I error describes that probability of elements of a given population to be shown by statistical tests not to be a part of the given population being tested. The type II error describes the probability that some part of an unknown population appears to be a part of the tested population. Both of these errors are attributable to random errors and the statistical power of the tests. This human measurement error is not a random error.

It is an error generated by a human inspector. The magnitude of the error is directly related to the physical, and possibly mental, skills of the inspector.

Even if this theory could not be proven to be general, but held to certain constraints such as type of measurement instrument, tightness of specification tolerances, ranges of dimensions, or combinations of any of these parameters, the significance of the development of a technique to wash out the biased variation from the true process variation could still offer substantial monetary rewards.

Continuous Process Monitoring

In the fields of continuous manufacturing processes the effects of human measurement errors toward establishing whether or not the process is in control are not very much different from those effects discussed previously in the section on Acceptance Sampling. If measurement errors bias the statistical results of a random sample of the product of the process to erroneously show the process to be out of control, or vice-versa, then some adjustments are or are not made to the process as dictated by the statistical results. How long the process then is allowed to operate in this out of control state will directly affect the potential monetary loss to the company.

This potential loss to the company with continuous manufacturing processes probably will be much harder to account for than the similar loss to a job lot manufacturer. This is assumed because the job lot manufacturer has discrete and known quantities of losses, either discovered by himself or his customer. On the other hand, the continuous process manufacturer has less discrete entities to work with. When discovering that the process is really out of control when in fact the biased statistics showed it to be in control, and vice-versa, the manufacturer will wonder how long this has been going on and how many products were produced during this time. Given that he did know exactly how many and which products were made during this time, he is faced with the problem of deciding which recovery technique would cost less: 1) 100% inspection of each part in hopes of salvaging some acceptable ones; or, 2) rejecting the entire batch. Either choice results in a substantial loss to the company.

Prediction of the Error

In the two previous sections the theme was developed that if normal and expected human error in measurement could bias sampling statistics significantly to show erronously the process to be out of control, and vice-versa, the financial effects could be striking. If this theme was proven, its proof would not by itself be significant. If nothing could be done to estimate the amount of bias in order to reduce the apparent process variation down to the true process variation, then little has been offered.

The truly significant contribution to the field of quality control would be if the amount of this bias could be predicted, or estimated such that it could easily be washed out of the sampling statistics. If each inspector could periodically be tested on a jig of similar nature to the one used in the experiment discussed in this report, his own amount of measurement error could be estimated. This technique is quite analogous to testing the variation of a machine process in order to estimate its value. Once an inspector's variation is known, its effect on his sampling measurements can be predicted and eliminated so as not to bias the statistical tests. In this manner the value of the estimated process variation will be more exactly described by the statistical tests.

It is beyond the scope of this report to devise a prediction model for this human error. The real intention of this report is to try to isolate this human error and to see if it could bias the statistics describing a process variation. This discussion is intended to show the open-endedness of this area of research with the hope that future readers seeing validity of such a concept would wish to continue research in this area.

CHAPTER III

THE EXPERIMENT

The Participants

There were seven adult males who were active participants in this experiment. Five of the participants were full time machine laboratory employees of the Industrial Engineering Department at Virginia Polytechnic Institute. Four of them were considered good measurers because of their experience. However, general opinion among these participants was that some were better measurers than others. The sixth active participant was a laboratory technician in the Wood Testing Laboratory at Virginia Polytechnic Institute. The seventh active participant was a graduate student in the Industrial Engineering Department of Virginia Polytechnic Institute. These two active participants were not considered to be good measurers because of their lack of experience. However, they were chosen to be active participants to see if experience in measurement could have some bearing in the accuracy of human measurement.

The inactive participant was the author of this thesis. His function was to arrange for an active participant to take some measurements and to record the readings of the measurements.

The Measurement Jig

The measurement instrument selected was a one inch micrometer manufactured by L. S. Starrett Company. It bore the serial number T230. The micrometer was groved along its stem to mate with a specially made aluminum holder. This holder was permantly attached to the base of an American Gauge Company bench center, size 4" x 10", serial number 006182. When the groved micrometer was mated properly with the holder, it resided in a nearly vertical plane to the bench center with the spindle of the micrometer upright. The micrometer was free to move in a single line, up-down, or Y-axis direction. It was not free to move in a horizontal, or X-axis direction; nor was it free to rotate in any direction. Figure 1 illustrates this jig.

Also attached to the holder was a cold rolled steel keystop. Its purpose was to affix the measured part to a consistent position. The exact purpose of this keystop will be made clearer in the next two sections.

The Material of Measurement

Two groups of parts were selected for the measurement experiment. The only difference between the two groups were their diameters. The two diameters were 1/2 inch and 5/8 inch. The material was SAE72 Free Cutting Brass, cold rolled, and in bar stock form. Forty parts one inch in length were cut from each diameter of bar stock. Each of the parts in both groups were stamped with cardinal numbers ranging from one through forty on one of the ends. Both ends of each part were beveled to mate properly with the bench center spindles. The end of each part with the number was notched just short of the bevel in order to mate properly with the keystop attached to the holder. Figure 2 illustrates one of these parts.

The right hand spindle of the bench center was adjusted to accept a firm fit with the notched end of a part such that the keystop on the holder mated with the notch in the part to eliminate any rotation of the

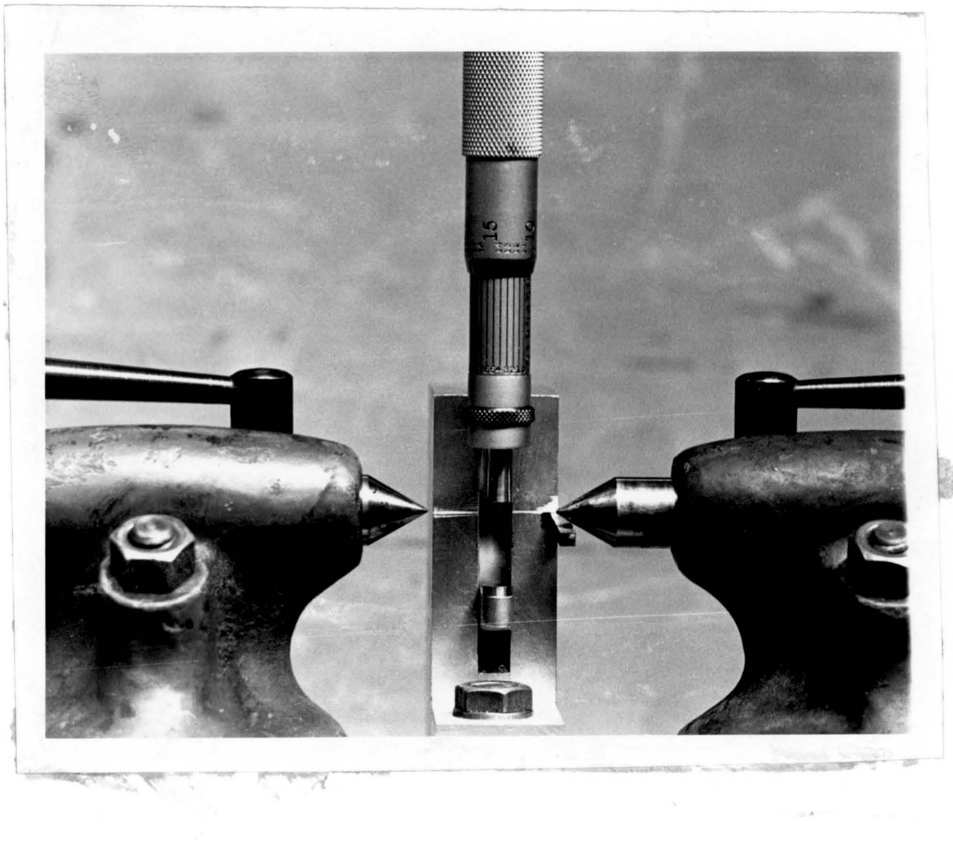

Figure 1. The measurement jig.

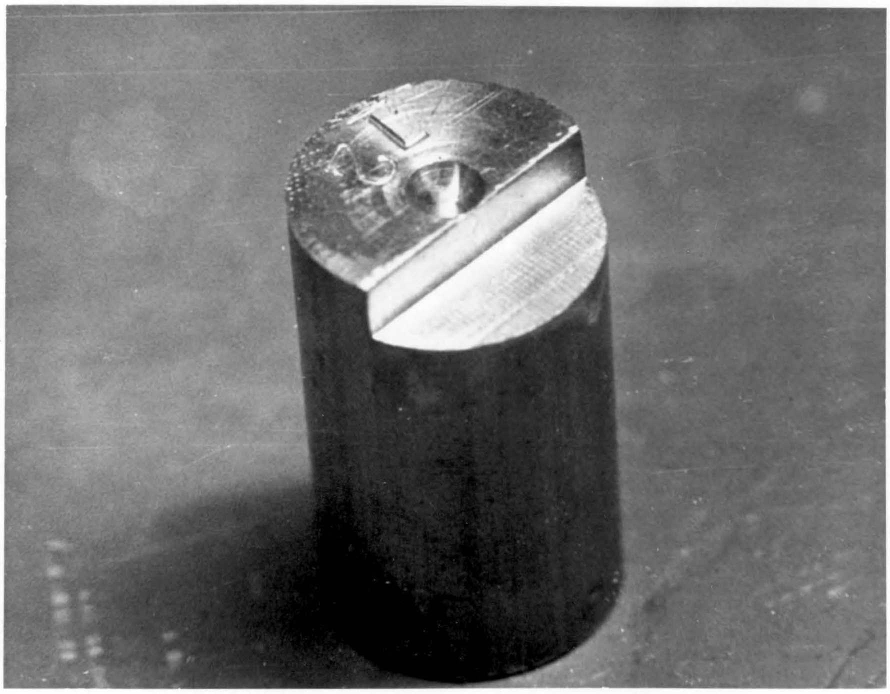

Figure 2. A brass part.

part. This right hand spindle of the bench center was locked into this position and not moved throughout the experiment. The left hand spindle had to be adjusted by the measurer to firmly place a part in the jig for a measurement. While placing a part between the spindles of the bench center the measurer had to adjust the micrometer in the vertical directions to properly place the part. Once a part was properly positioned and the left hand spindle of the bench center locked into place the measurer then was free to adjust the micrometer to measure the diameter of the part. Figure 3 illustrates a part placed in the jig and ready for measurement.

The Physical Environment of the Experiment

Since the primary purpose of the experiment was to isolate and estimate human error, or variation, in measurement, several physical factors of such an experiment had to be controlled or eliminated in order to get as accurate an estimate as possible.

Temperature variations were known to cause expansion and contraction of metals and such a phenomenon could drastically affect the results of this experiment. Therefore, in order to control this temperature effect, a temperature and humidity controlled environment was selected for the conduction of the experiment. The Wood Working Department in McBryde Hall on the Virginia Polytechnic Institute campus allowed the measurement jig and the parts to remain within their temperature and humidity controlled Wood Testing Laboratory during the several weeks of this experiment. The jig and the parts never were removed from this room during the testing phase. All measurements were conducted in this room. The temperature was maintained at 70°F. and the humidity at 30%. A continuous graphing device

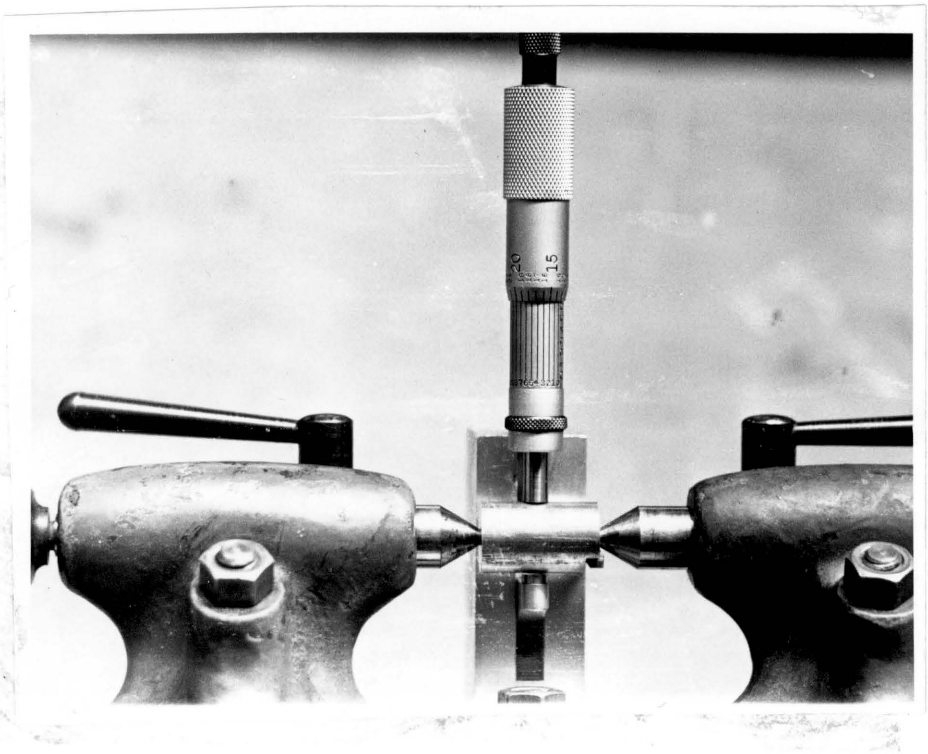

Figure 3. The measurement jig and part in place.

used to record temperature and humidity over time showed a maximum temperature variation of 1°F. from 70°F. and a maximum humidity variation of 3% from 30%.

The other physical variation of major concern that could drastically affect the results of this experiment was the expected variation in the diameter of any one part. One of these cylindrical parts could have an infinite number of different physical diameters to measure with a micrometer, e.g. each physical measurement would cause the micrometer to touch two different spots on the surface of the part. Because of this and because of the fact that no known process can make a completely uniform part, it was necessary to design the experiment such that the same physical diameter of any one part was measured repeatedly. If this was not controlled, then this diameter variation of the physical part could significantly affect the results of an estimate of human variation in measuring this part.

The rigid restrictions of the jig, the position and movement of the part to be measured, and the micrometer used to measure the part guaranteed, as closely as possible, that the micrometer touched a part at the same two points each time that particular part was placed in the jig and measured. In effect, the same physical diameter of any part was measured repeatedly by all the active participants, thus significantly reducing, if not eliminating, any process variation within one part.

The Random Sample

Four separate measurement tests were conducted for each active participant. Each test consisted of measuring ten parts four times each.

Two tests were conducted for the 1/2 inch diameter parts and two tests for the 5/8 inch diameter parts.

In order to reduce human bias either by the active participant and/or the inactive participant, a random ordering sample selection work sheet was designed to create a set of ten parts to be measured and the order of their measurement just before the active participant made the measurements. These work sheets for each of the active participants are included in Appendix A.

A random number table was used to select the part numbers and the ordering of the measurements. First the numbers of the ten parts from the total population of forty of the same size were selected randomly. The parts' respective numbers were recorded under the column headed PART NO. Then, the sequence of the measurements was determined randomly such that all parts were not necessarily measured four times consecutively. The sequence ranging from 1 through 40 was recorded in the section labeled RANDOM ORDERING. Intuitively, it was felt that if the active participant was allowed to measure each part four times consecutively that he would tend to bias his second, third, and fourth readings having just "determined the correct diameter" on his first reading.

The Testing Procedure

The date and time of the selection of an active participant to conduct a measurement test was simply dependent upon the desired convenience of the active participants and the inactive participant. There was no particular sequence to the selection of an active participant. All active participants were not required to have the same number of tests completed before proceeding to the next test. The active participants generally did alternate measurement tests for the 1/2 inch and 5/8 inch diameter parts. The active participants generally did not attempt more than one test per day. The entire testing period started on April 14, 1965 and ended on June 2, 1965. All tests were conducted under the direct supervision of the inactive participant. All tests were conducted in the Wood Testing Laboratory.

The active participants were asked by the inactive participant to measure as accurately as possible. No tolerance limits for the parts measured were quoted to the active participants. They were aware of the nominal dimensions of the diameters of the parts measured.

The inactive participant selected each part in the order dictated by the previously prepared random ordering sample selection work sheet. The part was given to the active participant who properly seated the part into the jig. When the active participant felt he had adjusted the micrometer to get a proper reading of the diameter of the part, he would read the micrometer to within a ten-thousandth of an inch and call out the reading to the inactive participant who would record the reading onto the work sheet. The active participants were allowed the option of using the rachet on the micrometer. Then the active participant would unseat the part and return it to the inactive participant. The inactive participant would place this part back into the group of parts and then select the next part in sequence, being careful not to let the active participant see that the very same part may have been selected again.

CHAPTER IV

STATISTICAL ANALYSIS TECHNIQUES

Analysis of Variance

Since the objective of this experiment is to isolate the contribution of human error in measurement, the key variable sought is a statistic which gives an estimate of this error. In Chapter IV, the measurement jig and the testing procedure were shown to be designed to contain the human error in the within sample variation. In the rigors of statistical theories, this experiment is defined to be one that can be tested by the Random Effects model of a One-Way Analysis of Variance (4).

Table I illustrates the Analysis of Variance, referred to also as ANOVA.

The sample calculations for the terms within Table I are included in Appendix B.

Since the within piece, or within sample, variation of the experiment should describe the human error, then the expected mean square of the within pieces variation, σ_ε^2, will be an estimate of this error.

Since this experiment fits the Random Effects model of a One-Way Analysis of Variance, the process variation of the pieces themselves, σ_p^2, can also be estimated. Since $MS_p = \sigma_\varepsilon^2 + 4\sigma_p^2$ and since MS_ε gives an estimate of σ_ε^2, then $\sigma_p^2 = \dfrac{MS_p - \sigma_\varepsilon^2}{4}$. (4)

Statistical F-tests

Once σ_ε^2, the human measurement error, for both sized pieces is

Table I

Analysis of Variance

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	Expected Mean Squares
mean	1	SS_μ	MS_μ	
among pieces	19	SS_p	MS_p	$\sigma_\varepsilon^2 + 4\sigma_p^2$
within pieces	60	SS_ε	MS_ε	σ_ε^2
TOTAL	80	$SS_\mu + SS_p + SS_\varepsilon$		

estimated for each active participant, F-tests can be made on these variances. Specifically, the null hypothesis, H_o, is that σ_ε^2 for the 1/2 inch pieces is equal to σ_ε^2 for the 5/8 inch pieces for each active participant. The alternate hypothesis, H_1, is that these variances are unequal. If the null hypothesis is rejected, then the active participant's measurement error for the 1/2 inch pieces is different from his measurement error for the 5/8 inch pieces (4).

Similar F-tests can be made on the measurement error estimates of the experienced active participants versus the inexperienced active participants. Rejection of the null hypothesis that these measurement errors are equal would indicate that inexperience does affect measurement error.

Once σ_ε^2, the measurement error, and σ_p^2, the true process variation, are estimated from the analysis of variance formulae, the relative magnitude of this measurement error in the between sample, or apparent process, variation can be analyzed. This analysis is not based on rigorous statistical tests. Rather, it is an "eyeballing" of these estimates in order to make some observations.

The populations of the pieces from which the samples were randomly drawn were considered to have a process variation. In the real world of manufacturing processes, these process variations will exist and are assumed not to create a significant interaction with the human errors.

CHAPTER V

ANALYSES OF RESULTS

Tabulated Variance Estimates

Table II summarizes the estimates for human error, σ_ε^2, and process variation, σ_p^2, for each active participant. These results were calculated from the data in complete form. That is to say that no unusual measurements were eliminated from the calculations.

By briefly inspecting these results, one group of statistics, the process variation for σ_p^2 for the 1/2 inch pieces, show Hodge, Mangum, and Simmers to have results not generally similar to the other active participants. A similar situation exists for σ_p^2 for the 5/8 inch pieces for Hodge and Smith. Later sections deal with investigations into these situations, some recalculations are done, and some interesting results ensue.

Effect of Process Variation

By inspection of the raw data for Hodge, Mangum, and Simmers for the tests on the 1/2 inch pieces, several pieces commonly measured by these three showed to have a nominal dimension quite unlike the rest of the pieces. Further investigation showed one of the other measurers to have encountered some of these pieces that were not representative of the population.

These unrepresentative pieces, numbers 11, 25, and 31, were eliminated from the raw data and new calculations were made on these four

Table II

Initial Estimates for σ_ε^2 and σ_p^2

Active Participant	1/2 Inch Pieces		5/8 Inch Pieces	
	σ_ε^2	σ_p^2	σ_ε^2	σ_p^2
Dillon	0.8750	2.7325	1.5417	1.4922
Gray	0.4667	3.1307	0.6333	0.4312
Henderson	0.8458	0.5272	1.9750	1.9076
Hodge	1.8333	10.2285	1.0583	8.1361
Mangum	1.4042	9.4074	1.9833	1.0331
Simmers	0.1833	6.0726	0.2833	0.2943
Smith	2.5708	2.1762	1.9333	0.0687

active participants. Table III shows these results relative to the initial calculations for the 1/2 inch pieces.

By "eyeballing" these results, it appears than an elimination of a particular 5 to 10% of the sample size significantly reduces the process variation estimate, σ_p^2. At the same time the measurement error estimate is only slightly affected. F-tests on the two estimates of the process variations give the following results:

$$H_o: \sigma_p^2 \text{ (uncorrected)} = \sigma_p^2 \text{ (corrected)}$$

$$H_1: \sigma_p^2 \text{ (uncorrected)} \neq \sigma_p^2 \text{ (corrected)}$$

$$F_o \text{ (Hodge)} = \frac{10.2285}{3.7740} = 2.69$$

$$F_o \text{ (Mangum)} = \frac{9.4074}{3.5503} = 2.65$$

$$F_o \text{ (Simmers)} = \frac{6.0726}{2.1850} = 2.77$$

$$F_o \text{ (Smith)} = \frac{2.1762}{0.5857} = 3.70$$

Setting an $\alpha = 0.05$, the upper limit is $F_{1-\frac{\alpha}{2},\ 19,17} = 2.57$. All four tests give an F_o which exceeds the upper limit. Thus, all four null hypothesis are rejected. The corrected process variations are not the same for the uncorrected process variations.

Similar F-tests on the two estimates for the measurement errors give the following results:

$$H_o: \sigma_\varepsilon^2 \text{ (uncorrected)} = \sigma_\varepsilon^2 \text{ (corrected)}$$

$$H_1: \sigma_\varepsilon^2 \text{ (uncorrected)} \neq \sigma_\varepsilon^2 \text{ (corrected)}$$

Table III

Corrected Estimates for σ_{ε}^2 and σ_p^2

Active Participant	Initial		Corrected		Pieces Removed
	σ_{ε}^2	σ_p^2	σ_{ε}^2	σ_p^2	
Hodge	1.8333	10.2285	1.9630	3.7740	11, 31
Mangum	1.4042	9.4074	1.4722	3.5503	11, 25
Simmers	0.1833	6.0726	0.1930	2.1850	25
Smith	2.5708	2.1762	2.8565	0.5857	11, 25

$$F_o \text{ (Hodge)} = \frac{1.9630}{1.8333} = 1.07$$

$$F_o \text{ (Mangum)} = \frac{1.4722}{1.4042} = 1.05$$

$$F_o \text{ (Simmers)} = \frac{0.1930}{0.1833} = 1.06$$

$$F_o \text{ (Smith)} = \frac{2.8565}{2.5708} = 1.11$$

Setting an $\alpha = 0.05$, the upper limit is $F_{1-\frac{\alpha}{2}, 59,59} = 1.67$. The lower limit is $F_{\frac{\alpha}{2}, 59,59} = 0.60$. All four tests give an F_o which falls within these limits. Thus, the null hypothesis is accepted for all four tests. The corrected estimates of measurement error cannot be shown to be different from the uncorrected estimates of measurement error.

In Chapter IV, it is stated that it was assumed that process variations do not have a significant interaction with the human error. This assumption appears to be supported by these results. The rather large deviation in the process variations due to the unrepresentative pieces did not create any significant deviations in the human error estimates.

Magnitude of Measurement Error

Using the corrected calculations for the estimates for the process variation and the human error, a ratio between these two estimates for each size piece for each active participant was calculated. Table IV illustrates these estimates and the ratios.

The ratio is calculated by dividing the measurement error estimate, σ_ε^2, into the process variation estimate, σ_p^2. A ratio greater than 1.00

Table IV

Corrected Estimates for σ_{ε}^2 and σ_p^2 and Ratios

Measurer	1/2 inch		Ratio	5/8 inch		Ratio
	σ_{ε}^2	σ_p^2		σ_{ε}^2	σ_p^2	
Dillon	0.8750	2.7325	3.12	1.5417	1.4922	0.97
Gray	0.4667	3.1307	6.71	0.6333	0.4312	0.68
Henderson	0.8458	0.5272	0.62	1.9750	1.9076	0.97
Hodge	1.9630	3.7740	1.92	1.0583	8.1361	7.69
Mangum	1.4722	3.5503	2.41	1.9833	1.0331	0.52
Simmers	0.1930	2.1850	11.32	0.2833	0.2943	1.04
Smith	2.8565	0.5859	0.21	1.9333	0.0687	0.04

signifies that the measurement error estimate is less than the process variation estimate.

In the 1/2 inch pieces experiments, only Henderson and Smith showed a ratio less than 1.00. All others had ratios of nearly 2.00 or greater.

However, in the 5/8 inch pieces experiments, Dillon, Gray, Henderson, Mangum, and Smith showed ratios less than 1.00. Simmer's ratio was very nearly 1.00, but Hodge's ratio was 7.69.

Comparing each active participant's measurement error estimate for the 1/2 inch pieces to the 5/8 inch pieces, all but Hodge and Smith showed increases in this estimate going from the 1/2 inch pieces to the 5/8 inch pieces. In a similar comparison for process variations all but Henderson and Hodge showed decreases in their estimates for this variation going from the 1/2 inch pieces to the 5/8 inch pieces.

Analysis of Process Variations

From the estimates of the process variation for the 1/2 inch and 5/8 inch pieces shown by the active participants, it appears that the process variation for the 5/8 inch pieces is less than that of the 1/2 inch pieces. That is to say that the process that produced the 5/8 inch pieces held closer tolerances in producing the bar stock from which these pieces were produced than did the process that produced the bar stock for the 1/2 inch pieces.

However, Hodge shows a process variation quite large and quite unlike that shown by the other active participants for the 5/8 inch pieces. By inspection of his raw data, particularly in his measurements on May 27, 1965, it can be seen that he gave fairly consistent readings that were quite large. In other words, he apparently gave a very loose touch to the micrometer and did not approach the true nominal dimension as closely as the other active participants did. In effect, his accuracy was not good. His precision, or consistency to give the same readings, was not any more out of line than that shown by the other active participants. These loose readings on May 27, 1965, coupled with somewhat tighter readings on April 19, 1965, thus created an estimate of the process variation which was not descriptive of the process at all.

The other differences in the process variations, both for the 1/2 inch and 5/8 inch pieces, as described by the estimates calculated from each measurer's data can "generally" be ignored. It was shown what a drastic effect can be made in the process variation estimate by simply removing one or two of twenty samples that appear to be out of the norm. These other differences in the process variation estimates can be related to the minute differences in the nominal dimension of each piece measured and to the random sampling of the pieces to be measured from the total population.

If each active participant had measured the same twenty pieces, the estimates of the process variation for each size of pieces shown by all participants would probably be very close, assuming that all measurers had the same general accuracy.

Analysis of Measurement Error

It was indicated in the section Magnitude of Measurement Error in this chapter that two of seven active participants showed measurement error estimates greater than their respective process variation estimates for the 1/2 inch pieces. On the other hand, five of seven active participants showed measurement error estimates equal to or greater than their respective process variations estimates for the 5/8 inch pieces.

For the 1/2 inch pieces, Simmers had the smallest measurement error, 0.1930, and Smith had the largest error, 2.8565. These upper and lower cases create a 15:1 ratio. For the 5/8 inch pieces, again Simmers had the smallest measurement error, 0.2833, and Mangum had the largest error, 1.9833. These upper and lower cases create a 7:1 ratio. As a group, the hypothesis can be drawn that the active participants were more consistent for the 5/8 inch pieces. This seems to be the case because of the 7:1 ratio describing the spread of error estimates for the 5/8 inch pieces. However, if the active participants error estimates are averaged, it is found that the average σ_{ε}^{2} for the 1/2 inch pieces is 1.2389 and for the 5/8 inch pieces is 1.3470. Thus the hypothesis can be drawn that, although the group was more consistent for the 5/8 inch pieces, the group was more precise for the 1/2 inch pieces.

Not being able to make a statistical significance test on the measurement error creates difficulties in concluding whether or not measurement error is significant. There are no standards indicating the proportion of process variation which measurement error should exceed in order to become significant. Thus any such standard must be arbitrarily set. It seems reasonable to hypothesize that if the magnitude of the measurement error estimates equals or exceeds the magnitude of the estimate of the process variation then the measurement error is significant. This is the standard used in this analysis.

Within either size, the σ_ε^2 values for each active participant show that each one obtains an estimate generally quite different from the others, with two possible exceptions. For example, in the 1/2 inch pieces, Dillon and Henderson gave σ_ε^2 values fairly close to one another; in the 5/8 inch pieces, Henderson and Mangum gave values of σ_ε^2 that were quite close. Generally, the hypothesis can be drawn that each active participant's σ_ε^2 is unique for himself, and is dependent upon his physical and mental skills.

Comparing each active participant's σ_ε^2 value for the 1/2 inch and 5/8 inch pieces shows that the σ_ε^2 for one size is not close to the σ_ε^2 for the other size. The closest cases show a difference of approximately 50 percent. And, pointed out earlier, the σ_ε^2 values for the 5/8 inch sizes are generally larger than the same estimate for the 1/2 inch size. The two exceptions to this rule, Hodge and Smith, both fall into unique categories. Hodge, pointed out earlier, gave a unusally large estimation of the process variation due to his loose handling of the micrometer. Smith, as will be pointed out shortly, is apparently the most inconsistent measurer of the group.

F-tests on the measurement error estimates for the two sized pieces give the following results:

$$H_o: \sigma_\varepsilon^2 \text{ (1/2 inch pieces)} = \sigma_\varepsilon^2 \text{ (5/8 inch pieces)}$$

$$H_1: \sigma_\varepsilon^2 \text{ (1/2 inch pieces)} \neq \sigma_\varepsilon^2 \text{ (5/8 inch pieces)}$$

$$F_o \text{ (Smith)} = \frac{2.8565}{1.9333} = 1.48$$

$$F_o \text{ (Mangum)} = \frac{1.4722}{1.9833} = 0.742$$

$$F_o \text{ (Gray)} = \frac{0.4667}{0.6333} = 0.737$$

$$F_o \text{ (Dillon)} = \frac{0.8750}{1.5417} = 0.568$$

$$F_o \text{ (Simmers)} = \frac{0.1930}{0.2833} = 0.681$$

$$F_o \text{ (Hodge)} = \frac{1.9630}{1.0583} = 1.86$$

$$F_o \text{ (Henderson)} = \frac{0.8458}{1.9750} = 0.428$$

Setting an $\alpha = 0.05$, the upper limit is $F_{1-\frac{\alpha}{2}, 59,59} = 1.67$. The lower limit is $F_{\frac{\alpha}{2}, 59,59} = 0.600$. The F_o's for Smith, Mangum, Gray, and Simmers fall within these limits. The null hypothesis is upheld in their tests. Their estimates of measurement error for the two sized pieces are not different. However, the F_o's for Dillon, Hodge, and Henderson fall outside these limits. The null hypothesis is rejected in their tests. The estimates of the measurement error for the 5/8 inch pieces for Dillon and Henderson are greater than their respective estimates of the measurement error for the 1/2 inch pieces. Hodge gives results just the opposite of Dillon and Henderson. His estimate of measurement error for the 1/2 inch pieces is larger. From these results, the hypothesis can be stated That an active participants' measurement precision can differ significantly with respect to a change in the nominal dimension being measured.

By inspecting the ratios in the table shown in the section Magnitude of the Measurement Error, it can be seen that Simmers had the smallest value for σ_ε^2 for both sizes. Apparently, he was the most precise of all the active participants. In both sizes, his ratio was greater than 1.00 meaning that his measurement error was less than the process variation. However, for the 5/8 inch pieces this ratio was 1.04 which can hardly be discounted as not being a significant measurement error for this size.

Further inspection of this table shows that Smith's ratios for both size pieces were the lowest of all the active participants. This means that his measurement error was considerable greater than the process variation. His measurement error would be considered significant relative to the process variation. Henderson, who was considered the best measurer by all the other active participants, gave results that also showed his measurement error to be greater than the process variation for both size pieces.

Hodge and Mangum were the inexperienced active participants. Smith was more experienced in measuring than Hodge and Mangum but was not considered to be a good measurer. These three active participants are grouped into the "inexperienced" category.

In order to test whether or not experience can affect measurement error, each of the two groups of measurers' error estimates are averaged for each size of pieces. These averages are:

A. Experienced measurers

1. Average σ_ε^2 (1/2 inch pieces) = 0.5951
2. Average σ_ε^2 (5/8 inch pieces) = 1.1083

B. Inexperienced measurers

1. Average σ_ε^2 (1/2 inch pieces) = 2.0972

2. Average σ_ε^2 (5/8 inch pieces) = 1.6583

F-tests on the average measurement error estimates for the two groups of measurers give the following results:

H_o: σ_ε^2 (experienced measurers) = σ_ε^2 (inexperienced measurers)

H_1: σ_ε^2 (experienced measurers) ≠ σ_ε^2 (inexperienced measurers)

$$F_o \text{ (1/2 inch pieces)} = \frac{0.5951}{2.0972} = 0.283$$

$$F_o \text{ (5/8 inch pieces)} = \frac{1.1083}{1.6583} = 0.669$$

Setting an $\alpha = 0.05$, the upper limit is $F_{1-\frac{\alpha}{2}, 59,59} = 1.67$. The lower limit is $F_{\frac{\alpha}{2}, 59,59} = 0.600$.

The test for the 1/2 inch pieces gives an F_o below the lower limit. The test for the 5/8 inch pieces gives an F_o just inside the lower limit. The null hypothesis is rejected for the 1/2 inch pieces. Lack of experience does not create less precision is measurement for the 5/8 inch pieces. From these results, a general hypothesis can be stated that lack of experience in measurement can create less precise measurements. Or, in other words, an inexperienced measurer can have less precision in his measurements.

Significance of Measurement Error

From the ratio of σ_p^2 to σ_ε^2 test, it was shown that of the seven independent tests conducted for each of the two sized pieces that:

1. two active participants showed measurement errors greater than the process variation for the 1/2 inch pieces, and;

2. five active participants showed measurement errors greater than the process variation for the 5/8 inch pieces, and;

3. a sixth active participant gave a measurement error almost equal to the process variation for the 5/8 inch pieces.

Based on the standard assumed by the author, i.e., the measurement error is significant when it is equal to or greater than the process variation, then eight of the fourteen independent tests of this experiment showed that the active participants' measurement error was significant. From these results, the conclusion will be drawn that, in general, the active participants of this experiment show measurement errors that are significant.

Undoubtedly, many readers of this report will question the standard which was chosen. The standard could be conservative, especially in an environment where tight tolerances are specified for the product from a manufacturing process. Since the results of this experiment showed that the process variation's magnitude did not apparently affect the measurement error of an inspector, then small process variations, generally related to processes that create products with tight tolerances, could be much less than the measurement error. The between sample variation would then be greatly biased by the rather large error estimate mainly due to the human measurement error.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

In the foregoing chapters, the author established the question whether or not human error in measurement should be considered to be a significant variable in the quantitative aspects of Statistical Quality Control. A unique physical experiment was devised to test the skills of four experienced measurers of manufacturing processes and three inexperienced persons. The purpose of the experiment was to isolate the human measurement error from the process variation of the product being measured. If this measurement error could be isolated it was to be evaluated with respect to its significance toward affecting an apparent process variation. The stated objectives were to isolate the measurement error and to evaluate the significance of this measurement error relative to the apparent process variation in terms of:

1. experienced versus inexperienced operators, and

2. the size of the dimension measured in the range of 0.500 inches to 0.625 inches.

The author spent some time discussing the practical uses of positive results from this and future research on measurement error. The basic advantages to manufacturing industries would be monetary savings resulting in increased profits due to reductions of production losses directly attributable to statistics, biased by measurement errors, falsely showing the product to be outside of the tolerance specifications, and vice-versa. The author stated that the success of this and other research to prove that measurement error does bias quality control statistics is not the ultimate success. The ultimate goal would be the ability to predict, through some statistical model, what the human error variability will be so that it can be eliminated from statistical tests that describe the manufacturing process variation.

Next, the physical experiment was discussed in detail. The physical equipment and its environment was illustrated. The testing procedure was outlined, including the random sampling techniques used to reduce if not eliminate human bias from the experiment.

The statistical model used to estimate the human measurement error, σ_ε^2, and the process variation, σ_p^2, was described. F-tests used to evaluate these estimates were discussed. This discussion was not intended to discuss statistics as such. It was intended to show the direct relationship of the design of the experiment and the statistical models themselves.

Conclusions and Hypotheses

In Chapter V, the results of the experiment were analyzed and the following conclusions or hypotheses were drawn:

1. Process variations of the pieces being measured did not have a significant interaction with the human measurement error. Results showed that large significant decreases in process variation estimates only insignificantly increased the measurement error estimates.

2. The process variation of the two populations of sized pieces were not the same. The estimate of the process variation for the 5/8

inch pieces given by each active participant was generally smaller than the same estimate for the 1/2 inch pieces.

3. Hodge's poor accuracy of measurement for some of the 5/8 inch samples created a very large estimate of the process variation for that size. It was hypothesized that this poor accuracy directly created an estimate of this process variation which was not descriptive of the process variation at all.

4. The active participants as a group gave measurement error estimates for the 5/8 inch pieces which were more consistent than for the same estimates for the 1/2 inch pieces.

5. The active participants as a group were more precise for the 1/2 inch pieces. Their averaged σ_ε^2 for the 1/2 inch pieces was less than that of the 5/8 inch pieces.

6. With two possible exceptions, each active participant had measurement error estimate quite unlike the others. Each active participants' σ_ε^2 was unique for himself, and was dependent upon his physical and mental skills.

7. Three of the seven active participants showed estimates of measurement errors that significantly differed for the two sizes of pieces. Two showed larger measurement errors for the 5/8 inch pieces. One showed a larger measurement error for the 1/2 inch pieces. The hypothesis was drawn that an active participant's measurement precision, or error, can differ significantly with respect to a change in the nominal dimension being measured.

8. Simmers was concluded to be the active participant with the least measurement error.

9. Smith was concluded to be the active participant with the most measurement error.

10. The three inexperienced measurers were shown to have a significantly greater measurement error than the experienced measurers for the 1/2 inch pieces. However, both groups did not have significantly different measurement errors for the 5/8 inch pieces. The general hypothesis was drawn that experience in measurement can affect the measurement error, i.e., lack of experience can result in an increase in measurement error.

11. Based on the author's assumed standard for testing the significance of the active participant's measurement error, i.e., the estimate of the measurement error equals or exceeds the estimate of the process variation, the conclusion was drawn that these active participants show measurement errors that are significant.

All of these conclusions or hypotheses are drawn relative to this experiment and its active participants. Many of these conclusions were drawn from analyzing results in very simple and unsophisticated manners. The estimates for the human measurement error and the process variation were derived rigorously. Statistical F-tests were used to analyze the "experience" and "dimension" relationships.

One purpose of this experiment was to isolate the human measurement error in measuring the diameters of two sizes of cylindrical brass pieces. This was accomplished with a great deal of success.

Another secondary purpose of this experiment was to test the significance of this isolated measurement error with respect to its contribution to the between sample, or apparent process, variation. The between sample variation was successfully determined. The true process variation, σ_p^2, was successfully determined. The significance test of the process variation to the measurement error could not be rigorously defined, so an arbitrary standard was assumed by the author to allow a significance test to be conducted. This significance test was used to draw conclusions relative to the stated objectives of this research.

Recommendations

Several adjustments and expansions can be made to this experiment to improve the results, and possibly allow stronger conclusions to be drawn. Many of the recommendations are from errors of poor design of the experiment. These errors were not anticipated by the author during the design stage. Some of the recommendations are expansions of the analysis of the data which the author feels could be quite useful but were beyond the scope of this experiment.

The following errors of the experimental design should be eliminated for future experiments of this nature:

1) The author initially assumed that the process variations of the two sized pieces selected for this experiment were the same since they were produced of the same material by the same type of process. Future experiments should use machined parts instead of cold rolled parts to insure the same process variations for different sizes.

2) All measurements for each active participant should be conducted at one sitting. This should control the measurer's feel for the measurement instrument. If this is not possible, be certain that the measurer's physical activity before a session has been relatively light. Heavy

activity will cause the measurer to tighten down on the instrument more than normally.

3) Size of parts should be mixed in one sitting. This should further reduce any bias the measurer would have on trying to artifically hold consistent readings. And it should reduce any doubts concerning error estimates on varying sizes since his measurement error is being tested in a short time period, not over a span of several weeks, for all sizes.

4) The author had intended to use a statistical nested classification technique to analyse the data of this experiment. But because the process variations of the two sized pieces differed, this was not done. It was felt that the interactions of these two different process variations would give statistical results that would not be very good estimates. However, if future experiments can insure the same process variations for pieces of two different sizes, then the nested classification can be used. This statistical technique for two different sizes will give estimated mean squares for three sources of variation; observation within size; size within pieces; and between pieces. The estimates for σ_ε^2 and σ_p^2 can still be calculated, but σ_d^2, the variation due to dimension, can also be estimated. With σ_d^2 estimated, stronger conclusions could be drawn with respect to the effect of dimension changes and measurement errors.

The following recommendation is made with respect to further analysis of the data of this type of experiment:

A range of pseudo-tolerances should be established for each population of sized pieces. Set these tolerances such that one pair could be considered tight, one pair generally normal, and one pair rather loose. Analyze the results of the experiment with respect to each of the tolerance limits. In other words, show the break-even point where the contribution of the measurement error in the within and between sample variations do not show the random samples of the pieces outside the tolerance limits. Also show where these same samples fall within the tolerances by eliminating the measurement error from the between sample variation.

The author feels that the net result of this research should place some belief in the readers mind that human measurement error can directly bias statistics which describe a manufacturing process. This bias could go to the extreme to create false descriptions of the manufacturing process in question. The author strongly recommends that further research should be conducted to support or disprove these claims.

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APPENDICES

APPENDIX A

RANDOM ORDERING SAMPLE SELECTION WORK SHEETS

Table V

Random Ordering Sample Selection Work Sheet

Measurer - Dillon   Size 1/2"   Date 4/27/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	01	.5010	.5010	.5010	.5010	5	13	29	30
2	04	.5010	.5010	.5011	.5010	3	7	9	22
3	06	.5006	.5007	.5007	.5006	2	6	18	26
4	07	.5007	.5010	.5011	.5007	1	25	34	36
5	09	.5005	.5005	.5005	.5005	10	11	14	20
6	15	.5011	.5011	.5010	.5011	8	17	21	27
7	18	.5007	.5007	.5007	.5006	12	15	16	19
8	29	.5010	.5010	.5011	.5010	23	24	37	40
9	30	.5007	.5007	.5008	.5007	28	31	32	35
10	39	.5011	.5008	.5008	.5008	4	33	38	39

Table VI

Random Ordering Sample Selection Work Sheet

Measurer - Dillon Size 1/2" Date 5/13/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	05	.5010	.5008	.5007	.5007	1	7	12	35
2	14	.5006	.5005	.5007	.5005	8	26	28	31
3	15	.5007	.5007	.5007	.5006	5	30	36	40
4	17	.5010	.5008	.5007	.5010	14	34	37	39
5	18	.5007	.5005	.5007	.5006	18	22	29	32
6	24	.5007	.5007	.5008	.5007	2	3	19	21
7	27	.5006	.5006	.5007	.5005	6	9	11	23
8	36	.5010	.5008	.5008	.5007	4	16	20	27
9	38	.5006	.5005	.5005	.5006	15	17	24	25
10	39	.5007	.5007	.5008	.5007	10	13	33	38

Table VII

Random Ordering Sample Selection Work Sheet

Measurer - Dillon Size 5/8" Date 5/26/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	02	.6255	.6255	.6254	.6256	35	36	38	40
2	13	.6255	.6255	.6256	.6255	4	27	30	32
3	15	.6255	.6255	.6254	.6255	11	14	31	39
4	19	.6254	.6254	.6254	.6253	2	13	17	26
5	20	.6254	.6253	.6255	.6253	20	23	33	37
6	21	.6255	.6255	.6255	.6256	1	3	10	18
7	23	.6255	.6254	.6256	.6255	21	24	28	29
8	28	.6256	.6254	.6254	.6256	7	22	25	34
9	37	.6255	.6256	.6255	.6254	8	12	15	19
10	38	.6255	.6256	.6255	.6254	5	6	9	16

Table VIII

Random Ordering Sample Selection Work Sheet

Measurer - Dillon   Size 5/8"   Date 4/14/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	02	.6255	.6255	.6258	.6256	2	3	25	31
2	13	.6264	.6257	.6258	.6261	1	10	15	38
3	14	.6255	.6255	.6255	.6255	6	13	14	27
4	15	.6256	.6260	.6257	.6255	11	22	26	33
5	22	.6257	.6256	.6255	.6256	7	8	30	39
6	26	.6255	.6255	.6256	.6256	9	19	29	32
7	31	.6256	.6256	.6255	.6257	23	28	43	36
8	33	.6261	.6255	.6257	.6257	5	18	20	24
9	38	.6255	.6255	.6255	.6256	4	16	17	21
10	39	.6256	.6256	.6256	.6256	12	35	37	40

Table IX

Random Ordering Sample Selection Work Sheet

Measurer - Gray　　　　Size 1/2"　　　　Date 5/17/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	01	.5008	.5008	.5007	.5008	15	25	27	38
2	12	.5007	.5008	.5006	.5005	5	13	16	19
3	14	.5006	.5006	.5007	.5005	2	10	14	28
4	16	.5007	.5007	.5006	.5006	9	29	32	33
5	17	.5010	.5010	.5010	.5009	3	4	20	31
6	18	.5006	.5006	.5005	.5007	11	21	39	40
7	20	.5006	.5006	.5005	.5005	6	8	26	34
8	21	.5005	.5005	.5005	.5004	1	12	17	30
9	29	.5008	.5010	.5007	.5007	18	23	35	37
10	30	.5007	.5007	.5006	.5007	7	22	24	36

Table X

Random Ordering Sample Selection Work Sheet

Measurer - Gray Size 1/2" Date 5/7/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	03	.5005	.5005	.5006	.5005	14	33	39	40
2	04	.5011	.5011	.5011	.5011	21	22	24	34
3	08	.5007	.5007	.5008	.5007	5	36	37	38
4	15	.5011	.5011	.5011	.5011	1	18	27	31
5	23	.5005	.5006	.5006	.5007	11	25	29	30
6	26	.5007	.5006	.5006	.5007	2	12	32	35
7	32	.5007	.5007	.5008	.5008	8	13	19	23
8	34	.5010	.5009	.5009	.5009	3	4	6	16
9	35	.5006	.5006	.5006	.5007	9	15	26	28
10	39	.5009	.5008	.5008	.5009	7	10	17	20

Table XI

Random Ordering Sample Selection Work Sheet

Measurer - Gray Size 5/8" Date 5/28/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	04	.6253	.6253	.6254	.6253	6	7	14	30
2	09	.6256	.6255	.6255	.6256	17	21	29	35
3	12	.6254	.6254	.6255	.6254	9	11	12	22
4	13	.6255	.6254	.6255	.6254	1	5	36	39
5	15	.6255	.6254	.6254	.6254	3	13	18	26
6	32	.6255	.6255	.6254	.6255	10	19	25	32
7	34	.6255	.6254	.6254	.6254	2	34	38	40
8	35	.6254	.6254	.6255	.6255	4	16	20	23
9	37	.6254	.6254	.6254	.6255	8	24	27	28
10	40	.6255	.6254	.6255	.6255	15	31	33	37

Table XII

Random Ordering Sample Selection Work Sheet

Measurer - Gray | Size 5/8" | Date 5/27/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	08	.6254	.6258	.6256	.6256	1	8	18	19
2	14	.6254	.6253	.6254	.6255	6	10	16	22
3	19	.6255	.6255	.6254	.6254	2	12	17	24
4	20	.6253	.6255	.6255	.6254	7	23	30	34
5	22	.6255	.6255	.6255	.6256	14	27	37	40
6	24	.6256	.6254	.6254	.6255	3	4	13	32
7	25	.6255	.6255	.6255	.6256	21	36	38	39
8	35	.6255	.6256	.6255	.6256	5	9	11	15
9	36	.6259	.6255	.6255	.6256	25	28	31	35
10	40	.6256	.6256	.6256	.6256	20	26	29	33

Table XIII

Random Ordering Sample Selection Work Sheet

Measurer - Henderson | Size 5/8" | Date 5/26/65

Piece	Part No.	Measurements 1	Measurements 2	Measurements 3	Measurements 4	Random Order of Measurements 1	Random Order of Measurements 2	Random Order of Measurements 3	Random Order of Measurements 4
1	01	.6256	.6256	.6257	.6257	13	25	36	39
2	02	.6257	.6257	.6256	.6257	1	6	12	15
3	03	.6257	.6257	.6257	.6257	2	14	27	29
4	11	.6256	.6256	.6257	.6257	3	17	18	23
5	12	.6256	.6256	.6256	.6257	5	8	35	38
6	22	.6257	.6257	.6257	.6256	7	21	32	34
7	26	.6256	.6256	.6256	.6256	9	16	37	40
8	26	.6256	.6256	.6256	.6256	4	26	31	33
9	32	.6257	.6257	.6257	.6257	19	24	28	30
10	40	.6257	.6257	.6257	.6257	10	11	20	22

Table XIV

Random Ordering Sample Selection Work Sheet

Measurer - Henderson   Size 5/8"   Date 4/19/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	01	.6257	.6257	.6257	.6261	1	12	14	18
2	06	.6260	.6260	.6260	.6258	5	8	10	17
3	09	.6262	.6258	.6260	.6260	2	38	39	40
4	10	.6257	.6262	.6260	.6257	13	16	24	29
5	11	.6257	.6257	.6257	.6260	7	22	28	35
6	25	.6256	.6257	.6257	.6258	20	21	32	36
7	31	.6261	.6260	.6262	.6263	3	4	6	25
8	36	.6256	.6258	.6257	.6260	9	11	15	19
9	37	.6257	.6257	.6263	.6263	23	26	27	33
10	39	.6257	.6258	.6262	.6258	30	31	34	37

Table XV

Random Ordering Sample Selection Work Sheet

Measurer - Henderson | Size 1/2" | Date 5/10/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	05	.5012	.5011	.5013	.5011	26	32	33	39
2	14	.5010	.5010	.5010	.5010	5	24	27	29
3	15	.5012	.5012	.5013	.5014	9	12	13	14
4	21	.5010	.5010	.5010	.5010	8	11	20	36
5	23	.5010	.5010	.5010	.5011	1	10	17	22
6	26	.5011	.5010	.5010	.5010	3	6	21	28
7	29	.5012	.5012	.5012	.5012	7	16	23	25
8	30	.5010	.5012	.5011	.5010	15	18	19	37
9	37	.5010	.5010	.5010	.5010	2	4	31	35
10	38	.5010	.5010	.5010	.5010	30	34	38	40

Table XVI

Random Ordering Sample Selection Work Sheet

Measurer - Henderson   Size 1/2"   Date 5/7/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	01	.5011	.5011	.5011	.5011	6	8	18	26
2	02	.5012	.5012	.5012	.5012	7	19	33	36
3	07	.5014	.5010	.5012	.5012	12	21	27	29
4	09	.5010	.5010	.5010	.5010	22	24	39	40
5	10	.5010	.5011	.5010	.5010	10	14	16	30
6	22	.5010	.5010	.5011	.5014	20	35	37	38
7	24	.5011	.5010	.5010	.5011	4	31	32	34
8	28	.5015	.5010	.5010	.5010	2	11	17	25
9	32	.5010	.5010	.5011	.5011	9	13	15	23
10	37	.5011	.5010	.5010	.5010	1	3	5	28

Table XVII

Random Ordering Sample Selection Work Sheet

Measurer - Hodge | Size 1/2" | Date 5/19/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	03	.5006	.5008	.5005	.5006	29	32	38	39
2	06	.5008	.5007	.5008	.5007	13	24	30	31
3	08	.5007	.5010	.5008	.5007	1	8	16	26
4	10	.5007	.5009	.5008	.5007	4	14	18	19
5	11	.5002	.5002	.5002	.5002	10	17	20	23
6	18	.5010	.5010	.5010	.5010	2	21	27	28
7	27	.5010	.5008	.5010	.5006	5	22	34	40
8	31	.5000	.5002	.5002	.5000	6	11	12	35
9	37	.5007	.5010	.5008	.5007	15	33	36	37
10	39	.5010	.5010	.5010	.5010	3	7	9	25

Table XVIII

Random Ordering Sample Selection Work Sheet

Measurer - Hodge | Size 1/2" | Date 4/27/65

Piece	Part No.	Measurements 1	2	3	4	Random Order Of Measurements 1	2	3	4
1	03	.5010	.5014	.5007	.5007	10	22	37	39
2	15	.5012	.5013	.5013	.5013	1	7	16	27
3	17	.5012	.5013	.5013	.5013	13	14	19	29
4	19	.5010	.5011	.5010	.5010	8	11	17	21
5	22	.5011	.5011	.5010	.5010	5	18	33	35
6	24	.5010	.5015	.5015	.5012	3	15	25	26
7	27	.5008	.5010	.5011	.5010	4	23	28	30
8	32	.5011	.5014	.5015	.5011	2	20	31	32
9	34	.5013	.5012	.5012	.5011	34	36	38	40
10	37	.5011	.5011	.5010	.5011	6	9	12	24

Table XIX

Random Ordering Sample Selection Work Sheet

Measurer - Hodge | Size 5/8" | Date 5/27/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	07	.6261	.6263	.6262	.6262	12	20	32	40
2	12	.6260	.6260	.6261	.6261	3	4	9	28
3	14	.6256	.6260	.6261	.6261	7	8	15	23
4	25	.6263	.6261	.6263	.6262	26	34	37	38
5	26	.6261	.6261	.6262	.6264	14	18	19	39
6	27	.6262	.6260	.6262	.6262	21	22	29	33
7	29	.6256	.6260	.6260	.6260	1	2	6	10
8	30	.6262	.6262	.6263	.6263	5	16	17	25
9	31	.6261	.6263	.6260	.6262	11	24	30	36
10	38	.6262	.6263	.6262	.6264	13	27	31	35

Table XX

Random Ordering Sample Selection Work Sheet

Measurer - Hodge Size 5/8" Date 4/19/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	03	.6256	.6256	.6257	.6256	12	25	34	40
2	08	.6257	.6257	.6256	.6257	4	7	19	33
3	12	.6255	.6255	.6255	.6255	14	21	22	32
4	15	.6260	.6258	.6257	.6257	1	8	10	16
5	18	.6256	.6256	.6257	.6257	20	23	26	30
6	22	.6255	.6255	.6255	.6255	3	13	15	17
7	30	.6256	.6256	.6256	.6256	24	27	37	39
8	32	.6257	.6256	.6256	.6256	6	11	28	38
9	33	.6256	.6256	.6256	.6255	29	31	35	36
10	36	.6256	.6255	.6256	.6255	2	5	9	18

Table XXI

Random Ordering Sample Selection Work Sheet

Measurer - Mangum | Size 5/8" | Date 6/2/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	01	.6256	.6255	.6255	.6255	1	5	9	15
2	07	.6255	.6255	.6255	.6255	2	6	18	20
3	10	.6256	.6256	.6256	.6256	14	31	37	38
4	15	.6257	.6256	.6257	.6256	7	10	16	17
5	16	.6256	.6257	.6255	.6257	3	13	30	33
6	17	.6256	.6255	.6255	.6256	21	32	36	39
7	18	.6256	.6256	.6256	.6256	4	28	34	40
8	25	.6256	.6255	.6255	.6255	12	25	26	35
9	27	.6255	.6255	.6255	.6255	8	11	27	29
10	32	.6256	.6256	.6257	.6256	19	22	23	24

Table XXII

Random Ordering Sample Selection Work Sheet

Measurer - Mangum　　　　Size 5/8"　　　　Date 4/14/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	01	.6256	.6257	.6253	.6254	1	8	26	31
2	06	.6256	.6256	.6254	.6261	12	14	17	18
3	09	.6261	.6258	.6256	.6256	3	7	10	13
4	10	.6255	.6253	.6253	.6253	11	25	32	35
5	11	.6254	.6253	.6254	.6253	30	34	37	39
6	25	.6255	.6253	.6253	.6253	27	28	29	36
7	31	.6256	.6254	.6254	.6254	9	22	33	40
8	36	.6256	.6255	.6253	.6253	6	15	20	21
9	37	.6257	.6257	.6254	.6262	2	4	16	19
10	39	.6257	.6255	.6254	.6253	5	23	24	38

Table XXIII

Random Ordering Sample Selection Work Sheet

Measurer - Mangum Size 1/2" Date 5/19/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	04	.5012	.5010	.5013	.5013	3	8	23	24
2	11	.5002	.5003	.5002	.5001	5	12	29	39
3	16	.5010	.5009	.5010	.5010	21	26	32	33
4	17	.5012	.5012	.5012	.5012	7	20	28	37
5	20	.5007	.5009	.5009	.5010	6	25	35	40
6	21	.5007	.5004	.5007	.5007	10	13	27	38
7	22	.5008	.5011	.5010	.5011	2	30	34	36
8	24	.5009	.5008	.5009	.5009	15	16	19	22
9	25	.5000	.5002	.5001	.5000	1	17	18	31
10	35	.5008	.5007	.5007	.5007	4	9	11	14

Table XXIV

Random Ordering Sample Selection Work Sheet

Measurer - Mangum Size 1/2" Date 5/10/65

Piece	Part No.	Measurements 1	2	3	4	Rnadom Order of Measurements 1	2	3	4
1	08	.5009	.5011	.5011	.5013	5	6	20	25
2	09	.5007	.5006	.5007	.5007	22	31	35	40
3	18	.5008	.5013	.5014	.5016	4	8	12	13
4	19	.5011	.5010	.5010	.5010	14	24	28	34
5	21	.5007	.5006	.5007	.5007	3	7	19	33
6	22	.5012	.5012	.5012	.5012	1	18	29	36
7	30	.5009	.5009	.5009	.5009	10	15	27	30
8	36	.5009	.5010	.5010	.5011	2	23	32	38
9	37	.5009	.5008	.5008	.5008	9	11	16	17
10	40	.5011	.5008	.5009	.5008	21	26	37	39

Table XXV

Random Ordering Sample Selection Work Sheet

Measurer - Simmers | Size 1/2" | Date 5/13/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	03	.5005	.5005	.5005	.5005	4	15	18	21
2	06	.5006	.5005	.5006	.5006	19	23	30	37
3	08	.5006	.5005	.5006	.5006	8	29	32	38
4	09	.5005	.5005	.5005	.5005	3	34	35	36
5	20	.5007	.5006	.5006	.5006	24	27	39	40
6	22	.5009	.5008	.5008	.5008	4	6	13	33
7	27	.5006	.5006	.5006	.5007	1	14	25	26
8	29	.5009	.5009	.5009	.5009	16	22	28	31
9	34	.5009	.5009	.5009	.5009	2	7	12	17
10	37	.5006	.5006	.5006	.5006	9	10	11	20

Table XXVI

Random Ordering Sample Selection Work Sheet

Measurer - Simmers | Size 1/2" | Date 5/17/65

		Measurements				Random Order of Measurements			
Piece	Part No.	1	2	3	4	1	2	3	4
1	05	.5008	.5008	.5008	.5008	4	26	39	40
2	08	.5006	.5005	.5006	.5006	8	33	37	38
3	09	.5005	.5005	.5005	.5005	20	31	35	36
4	14	.5006	.5007	.5005	.5005	2	5	6	7
5	15	.5008	.5008	.5009	.5008	18	22	29	34
6	16	.5008	.5007	.5007	.5007	19	21	23	27
7	17	.5008	.5009	.5009	.5009	3	16	28	30
8	25	.4998	.4998	.4998	.4998	1	10	12	17
9	29	.5008	.5009	.5009	.5009	9	13	24	25
10	34	.5008	.5009	.5008	.5008	11	14	15	32

Table XXVII

Random Ordering Sample Selection Work Sheet

Measurer - Simmers   Size 5/8"   Date 5/27/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	02	.6254	.6255	.6255	.6255	4	26	39	40
2	05	.6253	.6254	.6254	.6254	8	33	37	38
3	09	.6256	.6256	.6256	.6256	20	31	35	36
4	12	.6253	.6254	.6254	.6254	2	5	6	7
5	16	.6255	.6255	.6255	.6255	18	22	29	34
6	23	.6254	.6254	.6255	.6255	19	21	23	27
7	25	.6254	.6254	.6254	.6254	3	16	28	30
8	35	.6255	.6255	.6255	.6255	1	10	12	17
9	36	.6254	.6254	.6255	.6255	9	13	24	25
10	40	.6255	.6255	.6255	.6255	11	14	15	32

Table XXVIII

Random Ordering Sample Selection Work Sheet

Measurer - Simmers | Size 5/8" | Date 3/19/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	02	.6255	.6254	.6255	.6254	6	10	28	35
2	04	.6253	.6254	.6254	.6253	9	17	22	24
3	11	.6254	.6255	.6256	.6255	15	16	34	38
4	12	.6255	.6255	.6254	.6254	13	20	26	37
5	13	.6256	.6256	.6255	.6254	2	7	21	29
6	20	.6254	.6254	.6254	.6255	4	8	11	14
7	29	.6254	.6254	.6254	.6255	18	19	30	31
8	30	.6255	.6255	.6255	.6255	23	27	32	39
9	31	.6256	.6256	.6255	.6254	1	3	5	12
10	36	.6254	.6255	.6255	.6255	25	33	36	40

Table XXIX

Random Ordering Sample Selection Work Sheet

Measurer - Smith | Size 1/2" | Date 6/2/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	02	.5008	.5005	.5004	.5004	5	33	38	39
2	09	.5004	.5003	.5002	.5004	21	25	28	30
3	11	.5000	.5000	.5000	.5000	3	9	15	22
4	13	.5005	.5005	.5006	.5006	8	12	17	24
5	15	.5003	.5005	.5001	.5005	4	10	29	36
6	16	.5008	.5004	.5004	.5005	6	34	35	37
7	20	.5004	.5004	.5005	.5004	14	27	31	32
8	25	.5000	.5000	.5000	.5000	1	13	18	20
9	26	.5004	.5004	.5006	.5002	11	23	26	40
10	38	.5004	.5004	.5002	.5004	2	7	16	19

Table XXX

Random Ordering Sample Selection Work Sheet

Measurer - Smith   Size 1/2"   Date 4/27/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	03	.5004	.5001	.5000	.5005	18	25	29	36
2	15	.5007	.5007	.5000	.5001	4	11	14	30
3	16	.5007	.5005	.5005	.5003	1	23	26	31
4	19	.5005	.5006	.5004	.5005	8	16	20	21
5	21	.5005	.5002	.5001	.5000	9	19	32	39
6	26	.5003	.5002	.5001	.5004	3	37	38	40
7	32	.5006	.5005	.5003	.5005	6	7	22	27
8	34	.5005	.5004	.5006	.5002	12	17	24	33
9	36	.5005	.5006	.5005	.5004	2	5	10	13
10	39	.5007	.5006	.5005	.5006	15	28	34	35

Table XXXI

Random Ordering Sample Selection Work Sheet

Measurer - Smith   Size 5/8"   Date 4/20/65

		Measurements				Random Order of Measurements			
Piece	Part No.	1	2	3	4	1	2	3	4
1	06	.6257	.6255	.6253	.6256	9	17	27	36
2	10	.6255	.6253	.6256	.6255	12	24	33	35
3	13	.6257	.6256	.6255	.6253	1	37	38	40
4	14	.6255	.6254	.6259	.6254	8	11	25	32
5	16	.6255	.6256	.6256	.6256	13	14	19	26
6	20	.6255	.6253	.6252	.6253	18	23	28	29
7	24	.6260	.6256	.6255	.6255	5	7	15	20
8	25	.6256	.6255	.6255	.6255	3	10	31	39
9	35	.6258	.6256	.6254	.6254	4	6	21	22
10	40	.6257	.6255	.6252	.6257	2	16	30	34

Table XXXII

Random Ordering Sample Selection Work Sheet

Measurer - Smith　　　　Size 5/8"　　　　Date 6/2/65

Piece	Part No.	Measurements 1	2	3	4	Random Order of Measurements 1	2	3	4
1	06	.6256	.6255	.6255	.6255	12	18	27	29
2	14	.6254	.6254	.6253	.6253	6	13	31	32
3	15	.6255	.6255	.6255	.6256	11	20	36	39
4	21	.6255	.6253	.6255	.6256	14	24	33	34
5	23	.6256	.6255	.6253	.6253	5	9	25	28
6	26	.6255	.6255	.6254	.6253	2	4	7	26
7	33	.6254	.6256	.6255	.6255	1	3	8	38
8	35	.6255	.6256	.6254	.6255	19	21	30	35
9	38	.6254	.6255	.6255	.6256	15	17	22	23
10	39	.6256	.6254	.6254	.6255	10	16	37	40

APPENDIX B

SAMPLE CALCULATIONS

APPENDIX B

Table I illustrates the Analysis of Variance formulae used in the analysis of this experiment. Below are sample calculations illustrating the use of these formulae. These calculations are for Gray's measurements on the 1/2 inch pieces. Since the common base for all the 1/2 inch measurements was 0.5000, this amount was subtracted from each individual measurement reading.

observations per piece = $n = 4$

number of pieces (samples) = $p = 20$

sum of observations/piece = $\Sigma T_i = 584$

sum of (observations/piece)^2 = $\Sigma T_i^2 = 18040$

sum of (individual observations)^2 = $\Sigma\Sigma Y_{ij}^2 = 4538$

(sum of individual observations)^2 = $G^2 = 341056$

sum of squares for pieces = $SS_p = \frac{\Sigma T_i^2}{n} - \frac{G^2}{np}$

$$= \frac{18040}{4} - \frac{341056}{80} = 246.8$$

mean squares for pieces = $MS_p = \frac{SS_p}{p-1} = \frac{246.8}{19} = 12.9895$

total sum of squares = $SS_t = \Sigma\Sigma Y_{ij}^2 - \frac{G^2}{np} = 4538 - 4263.2 = 278.4$

sum of squares for error = $SS_\varepsilon = SS_t - SS_p = 274.8 - 246.8 = 28.0$

$$MS_\varepsilon = \sigma_\varepsilon^2 = \frac{SS_\varepsilon}{np-p} = \frac{28.0}{60} = 0.4667$$

$$\sigma_p^2 = \frac{MS_p - MS_\varepsilon}{n} = \frac{12.9895 - 0.4667}{4} = 3.1307$$

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A STUDY OF HUMAN MEASUREMENT ERROR

IN A CONTROLLED EXPERIMENT FOR

MICROMETER MEASUREMENTS

Olaf Lee Gibson, Jr.

Abstract

This is an exploratory thesis. The objective of this thesis is to isolate human measurement error in a physical measuring environment. A secondary objective is to evaluate this measurement error, if successfully isolated, with respect to its effect of biasing statistical quality control tests that describe a manufacturing process.

The author of this report designed a specialized measurement jig that was used to isolate human measurement error. Specifically, the tests involved seven human inspectors making micrometer measurements of the diameters of cylindrical brass pieces. Several physical factors were rigidly held in control or eliminated by the design of the jig and the experimental process. This was necessary to obtain as accurate an estimate as possible of the human error.

The human measurement error in this experiment was successfully isolated. Further analysis of this measurement error led to the hypothesis that it probably can bias statistical quality control tests that describe a manufacturing process. This bias is reasoned to have a greater effect on statistics that describe processes with very close physical tolerances.