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PROCESS CAPABILITY DETERMINATION OF NEW AND EXISTING EQUIPMENT

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KEY WORDS: Process capability, statistical process control, statistics, equipment characterization.

PREREQUISITE KNOWLEDGE: Introductory statistics, some knowledge of manufacturing processes and equipment. This will generally be an experiment for an advanced class.

OBJECTIVES: To illustrate a technique for determining the process capability of new equipment, existing equipment, or testing laboratories. To illustrate a method of objectively determining wear and other changes in equipment used for small quantity production over a period of time. To present an example of the application of the technique.

INTRODUCTION

The objective of this paper is to illustrate a method of determining the process capability of new or existing equipment. The method may also be modified to apply to testing laboratories. Long term changes in the system may be determined by periodically making new test parts or submitting samples from the original set to the testing laboratory.

The technique described has been developed through a series of projects in special topics manufacturing courses and graduate student projects. It will be implemented as a standard experiment in an advanced manufacturing course in a new Manufacturing Engineering program at the University of Wisconsin-Stout campus.

Before starting a project of this nature, it is important to decide on the exact question to be answered. In this case, it is desired to know what variation can be reasonably expected in the next part, feature, or test result produced. Generally, this question is answered by providing the process capability or the average value of a measured characteristic of the part or process ± three standard deviations. There are two general cases to be considered: (1) the part or test is made in large quantities with little change or (2) the process is flexible and makes a large variety of parts. Both cases can be accommodated; however, the emphasis in this report is on short run situations.

GENERAL PROCEDURE

The first step in any investigation is to clearly define what is desired. Specifically, what measurements will give the most information about the process, can be measured with relative ease, will continue to be made for the foreseeable future, and relate directly to the quality of the part. Quite often, this step is done too quickly and the results do not give the desired information. It is suggested that extra time be taken to clearly define the specific problem.

Selecting the proper sample is the next step. For large runs of production parts or routine tests, the normally measured features of the part or the standard test samples can be used. A special part may have to be developed for short run, flexible machinery. This part should include a variety of features which incorporate as many of the functions of the machine as possible. One such part is illustrated later. For short run situations, a method can be used which focuses on the process, not the product.[1] One technique is to use the deviation from the nominal dimension as the measured characteristic rather than the actual dimension.[2] This allows measurements of various depth holes or different diameter rounds, etc. to be used to generate sufficient numbers for reasonable process capability estimates. These comparison procedures (comparing deviations from nominal dimensions for similar features) can be used to give a running process capability. Periodically, an original test sample can be produced to evaluate any undetected changes with time in the machine performance.

When testing laboratories are to be evaluated, a large number of identical samples are obtained from well characterized material. If more than one type of material is tested routinely, then representative samples of each should be included. About one-fourth of these are used initially and the rest are submitted over a period of time.

Each part produced may be measured but often a sample of the production lot is measured. In the latter case, it is important to randomize the part selection so the Laws of Chance will apply and the results will be valid. All of the testing laboratory specimens should be numbered sequentially (include all different materials) and a random sample selected comprising the initial one-fourth or so of the specimens. These should be submitted to the laboratory with instructions to run the specimens in the order listed. If the materials are sufficiently different, such as those requiring different load cells on a tensile machine, a stratified random sample may be required. The data from the initial measurements or test results can be used to determine the current, initial process capability. The process capability can be updated as new measurements are obtained.

For testing laboratories, a small number of original "standard" specimens can be blended into the normal production tests and the variation of test lab results with time evaluated. These results can be combined with the results for the normal production specimens to give a continuously updated process capability. It is suggested that test laboratory evaluations be discussed with the lab manager after the initial results are obtained before being generally distributed. Quite often there are explanations for unexpected results of which the investigator may be unaware. This also helps keep political peace within the company.

APPLICATION TO A MACHINE TOOL

Objective:

The Manufacturing and Industrial Technology Department of Arizona State University recently obtained a Fadal VMC-20 vertical machining center. Mr. Su was assigned to determine baseline measurements of the dimensional reproducibility of this machine as part of his Master of Technology project. Sample materials were two alloys commonly used in the department: 1018 cold rolled steel and 6061-T6 aluminum. The objective was to determine the initial dimensional reproducibility of the new machine, to determine if a difference exists between the two materials, and to quantify such a difference if one exists.

Procedure:

The machining center was obtained as a flexible component of a manufacturing cell and is not part of a line producing many of the same component. For this reason, a special part was designed to give a measure of the various machine capabilities and this part is shown in Figure 1. The overall nominal dimensions are 102 mm x 102 mm x 44.5 mm (4 inches x 4 inches x 1.75 inches). Each feature is dimensioned with respect to the center line or top surface but the numbers are not shown because of the clutter. The parts were machined to the same programmed nominal dimensions and these dimensions were then measured on a coordinate measuring machine. The deviations from the nominal dimensions were the characteristics of interest. In this way, the various linear dimensions could be combined with each other and likewise with the various circular dimensions. Each part is therefore capable of giving numerous samples for the calculation of the process capabilities.

Six machining processes were evaluated using the designed part:

1. End milling of the steps to preset depths.
2. End milling of steps to preset peripheral dimensions.
3. End milling circular interpolation clockwise in to preset outside diameters of cylinders and round corners.
4. End milling circular interpolation clockwise out for circular pockets and round corners.
5. Reaming the holes to preset diameters after center hole and pilot hole drilling.
6. The relative positions of the holes from the center lines of the part after reaming.

Two materials were used: 1018 cold rolled steel and 6061-T6 aluminum. The same basic program was used for each with variations based on published optimum machining conditions for each material.[3] These conditions were modified somewhat for the steel as a result of chatter problems with the initial part. The Fadal machining center was capable of holding the complete tool sets needed for both parts and, thus, loading tooling into the machine was not a factor in the results.

The initial experiment was designed to determine if there was a difference in dimensional reproducibility between the aluminum and steel at the 95% confidence level. A difference of 0.0076mm (0.0003 inches) was considered to be of practical significance and an initial standard deviation of 0.0051 mm (0.0002 inches) was used for the initial calculations. These values were estimated from experience and guessing. The standard deviations were checked after the first parts were machined and found to be higher for these parts, to vary with the process in question, and with the material. The number of test parts required was then recalculated. The calculations considered the number of features to be combined on each part and showed that six parts of each material were required to determine if a difference exists between the steel and aluminum. The machining order for two materials was determined by randomization. Each part blank was placed into the machine by hand.

Results:

The results of the machining tests are summarized in Table I.

TABLE I
Summary of Machining Results
Values are Variations from Nominal Dimensions mm (inches)

Aluminum--6061-T6:

Process	Average	Std Dev (σ)	Initial PC ($\pm 3\sigma$)	#meas
1	-0.0061 (-0.00024)	0.0053 (0.00021)	± 0.015 (± 0.0006)	36
2	0.0322 (0.00125)	0.0990 (0.00039)	± 0.0305 (± 0.0012)	36
3	0.0236 (0.00093)	0.0104 (0.00041)	± 0.0305 (± 0.0012)	36
4	0.0142 (0.00056)	0.0127 (0.00050)	± 0.0381 (± 0.0015)	36
5	-0.0338 (-0.00133)	0.0142 (0.00056)	± 0.0457 (± 0.0018)	24
5*	0.0310 (0.00122)	0.0051 (0.00020)	± 0.0152 (± 0.0006)	23
6	-0.0079 (-0.00031)	0.0135 (0.00053)	± 0.0419 (± 0.0017)	48

One hole in one part had a very high variation in process 5 and no assignable cause was found for this variation. The data for 5 were calculated using all results and 5 dropped the questionable reading. All of the readings were used in the comparisons.

Steel--1018 cold rolled

Process	Average	Std Dev (σ)	Initial PC ($\pm 3\sigma$)	#meas
1	0.0117	0.0117	± 0.0356	36
	(0.00046)	(0.00046)	(± 0.0014)	
2	-0.1540	0.0991	± 0.2970	36
	(-0.00607)	(0.00390)	(± 0.0117)	
3	-0.0478	0.0937	± 0.282	36
	(-0.00188)	(0.00369)	(± 0.0111)	
4	0.1460	0.1430	± 0.4270	36
	(0.00573)	(0.00562)	(± 0.0168)	
5	-0.0277	0.0610	± 0.0152	24
	(-0.00109)	(0.00024)	(± 0.0006)	
6	-0.0157	0.0236	± 0.0419	48
	(-0.00062)	(0.00093)	(± 0.0017)	

Each average is calculated from 24, 36, or 48 individual readings depending on the type of measurement. For example, there are six steps (one inside and five outside on each of the six parts) which were measured for Process 1 so 36 measurements were averaged. There are four holes in each part so Process 5 is the average of 24 readings. Two measurements were made for the position of each hole (x and y) with respect to the center of the part so 48 measurements were averaged for process 6.

The data were compared using the "z Test for Measurements" and the "Student's t Test" [4] and it was found that a significant difference existed between the aluminum and steel at the 95% confidence level for all processes measured except for processes 5 and 6. It should be noted that process 5 was the process with the one unexplained high reading and the comparison statistic was very close to the decision point. This would normally indicate that another one or two parts should be run but, at the time of writing this experiment, no free machine time was available to run these parts.

Thus, except for processes 5 and 6, the two populations cannot be combined and the process capability must be determined for each material. These data are listed in Table I.

Discussion:

It should be emphasized that the process capability of the machine in making a specific part will be greatly influenced by the cutting conditions used. This machine will be used for a variety of parts under a variety of cutting conditions as a class room teaching tool and it is difficult to derive process capability values for each situation. The cutting conditions used in this study were arbitrarily chosen using handbook data and may not represent the best conditions for precision cutting of a particular part for a specific application. These data do give a baseline to use for determining changes in the machine due to wear or other factors as the machine is used. The programs generated in this study can be used with the same, readily available materials at various future times and the process capabilities compared to the initial data presented above. Any wear should manifest itself as increases in the ± 3σ values.

Because no assignable cause could be found for the high reading in process 5 for the aluminum, the data point was included in the comparison between the steel and aluminum for this process.

Many authors consider a minimum of 50 readings to be necessary for an accurate process capability determination.[5] For the situation in this study, 24 to 48 readings were considered sufficient for initial process capability values. Additional readings will be obtained from the parts made in the classes which can be measured using the same techniques described here and the data combined with the appropriate process category. This will give a running process capability with the test parts being machined at regular intervals of machining time to spot check for wear or other changes in the equipment.

CONCLUSIONS

A method has been presented by which the process capability of machine tools, manufacturing processes, or testing laboratories can be evaluated. The method allows the continuous monitoring of the process capability over an extended time period by running similar standard parts periodically mixed in with normal production.

An example was presented for a Fadal VMC-20 vertical machining center. Initial process capabilities for six individual machining processes were determined using 6061-T6 aluminum and 1018 cold rolled steel and a specially designed part. It was also determined that 1018 cold rolled steel test parts had a statistically higher variation in machined dimensions than 6061-T6 aluminum at the 95% confidence level when each were machined using handbook values to establish the cutting conditions. The data generated can be used as a baseline to check for later wear or other machine changes by periodically machining similar parts from similar materials using the same NC program. Short run statistical techniques were used because this machine was purchased as a flexible tool for making a variety of parts in a classroom situation.

The process capabilities determined apply only to the test parts manufactured but additional data can be obtained from class projects and combined to give running process capability measurements for each individual function of the machine.

SAMPLE DATA SHEETS: Data should be gathered in a manner compatible to analysis using a computer spread sheet or database program. One suggestion is as follows:

Material	Process	Nominal meas	Actual meas	Difference
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----------	---------	----------	----------	--------------
"		"	"	"

SAFETY CONSIDERATIONS: There are no special safety considerations for this experiment but all safety practices common to the equipment or processes studied should be followed.

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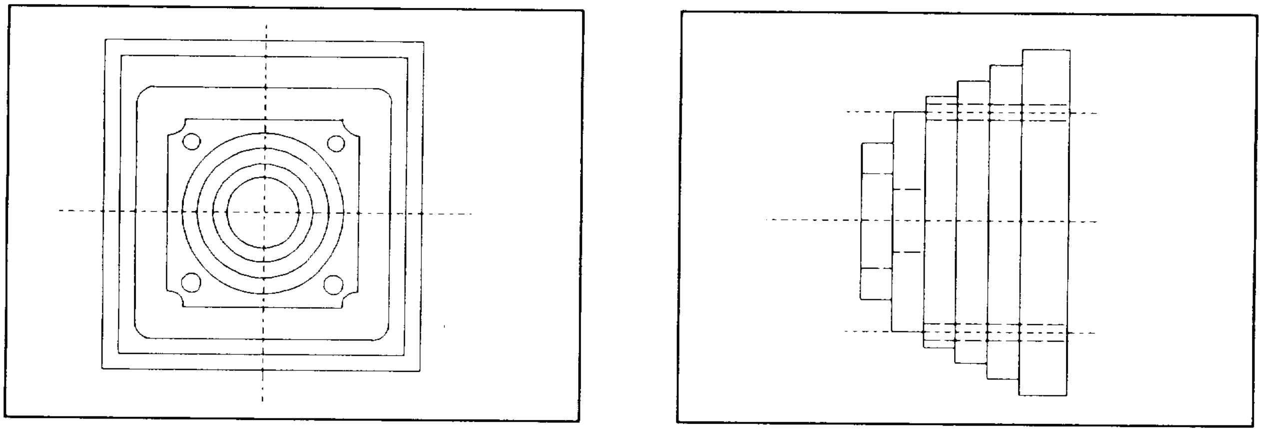

Figure 1: Top and side views of the specially designed part for the machining study.

INTRODUCTION TO USABLE STATISTICAL METHODS

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INTRODUCTION TO USABLE STATISTICAL METHODS

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KEY WORDS: Statistics, Process analysis, Statistics courses.

PREREQUISITE KNOWLEDGE: College algebra, Introductory manufacturing course helpful but not mandatory.

OBJECTIVES: Provide an introduction to statistics, experimental design, and data analysis for engineering and engineering technology students who do not have a full statistics course in their curriculum or who are not exposed to experimental design.

INTRODUCTION

The purpose of this paper is to present a description of a short course on usable statistical methods for students who are not exposed to a full statistical course. The course is designed to take approximately one fourth to one third of a semester (10 - 16 class hours) as part of a more general technical course such as a selected topics course in manufacturing. The need for a course of this nature is apparent when it is realized that many engineering programs do not require a statistics course and those courses which are required often do not include experimental design. Often, both students and faculty are not aware of basic statistical principles.

There are many introductory statistics courses offered by various departments with some campuses having four to seven seemingly similar courses.[1,2] A nonscientific, personal poll of students at two universities taking a variety of the introductory statistics courses of which I was aware all described the same course syllabi. A considerable amount of time is spent on basic number theory (mostly manipulating numbers which is not the same as understanding what the numbers mean) and more time on permutations and combinations. These are all good subjects but no time remained for discussing the basics of experimental design, random sampling, or the statistical evaluation of experimental data.

Personal experience in industry has shown that most manufacturing applications of statistics involve determining baseline process information (process capabilities) or comparing baseline information with the process performance after a controlled change. Generally, the results of the desired changes must be fairly large to be justified economically, particularly where new equipment must be purchased. Thus, techniques aimed at finding subtle differences among the data are usually not required.

The course described in this paper covers only the basics of probability and emphasizes experimental design and analysis.

GENERAL COURSE DESCRIPTION

Practical Statistics, Simply Explained by Langley[3] is the recommended text. This is a basic text which covers the fundamentals very well while the examples are easily updated, where necessary, by incorporating items from current news sources. Following the text, the course covers how to understand and interpret numerical data, basic probability theory, sampling, averages and scatter, experimental design, and significance tests.

This is a course in which items from current events add a generality to the topics which helps the students understand that the basic concepts of interpreting numbers are widely applicable. Occasionally some major events such as the oil crises of the seventies and eighties lead to many years of examples of media misuse of numbers on an almost daily basis. Currently, the debates over mandatory AIDS testing, gun control, and the President's budget offer regularly occurring topics. Sometimes it requires a bit more searching for appropriate examples. If you are teaching this course on a regular basis, you may pull examples from the news media as they appear over the year and save them for the class.

The concepts discussed in the early portion of the course are those which, in my experience, students have not understood during their earlier education. Students often become quite adept at manipulating numbers and equations without gaining any insight into what the numbers mean. The basic approach of the Langley text is how to avoid being misled by numbers. Students often find the other side of this topic to also be of interest, i.e. how to mislead others by the misuse of numbers. Either approach can be used to get the concepts across.

SPECIFIC TOPICS

Each of these topics can be covered in one or two 1 hour lectures.

Numbers:

The first chapter deals with being misled by arithmetical errors, false percentages, fictitious precision, misleading presentations, incomplete data, and faulty comparisons. Each of these topics can be related to other courses which the students are taking, particularly those with laboratory components such as physics or chemistry. For example, excessive significant digits resulting from students copying the answer directly from their calculators can be used as a prime example of fictitious precision. Generalizing mundane laboratory data to earth shaking, socially significant conclusions can be used to explain incomplete data or misleading presentations. Misleading presentations can also be illustrated by reference to the "low fat" competition going on in the grocery stores.

Langley states that these are all important causes of being misled by numbers but that the usual causes are biased samples and not considering the effect of chance on the numbers.

Probability:

Probability is introduced by a discussion of the Laws of Chance. This leads into the Binomial and Poisson's probability formula for describing the proportions of occurrence of two classes of events, i.e. on/off, go/no-go, yes/no, happens/doesn't happen. The normal probability formula is introduced to deal with continuous data. A brief discussion at this point covers the mean of the probability distributions and the scatter or variation about the mean. The main objectives for this topic are to introduce the probability distributions and the reasoning behind them rather than memorizing a formula.

Experimental Planning and Sampling:

I spend a considerable amount of time discussing the statement of the problem, planning the experiment, and devising an appropriate sampling plan. The problem statement is extremely important and is often made with little thought. A proper problem statement prevents wasted time and effort finding an possibly elegant solution to a non-problem or solving only a part of the problem. It also allows the proper generalization of the results. The importance of phrasing the problem in terms such as "...to determine the effect of.." rather than "...to prove the effect of..." is emphasized. This allows negative results (i.e. no difference with the treatments) to still be valid. Another important point is to state the problem so a path to the solution is apparent. If no path to the solution is apparent, restating the problem in different forms until a solution path is obvious is discussed. This also allows a better definition of what is sought.

The next step is to select the method of data analysis before the data are taken. In this manner, the data can be obtained in a form which fits the analysis method. An example of a lack of agreement would be to assume that the analysis will involve the binomial distribution but the experiment measures a continuously changing series of events which requires a normal distribution based analysis. The result of this would be an extra amount of data manipulation and less than satisfactory conclusions.

Sampling is a big area of misunderstanding. I have often seen situations where the student is simply told to go and take an appropriate sample with no further instructions. The major objective in this section is to emphasize the importance of a properly designed sampling procedure.

If the whole population is measured, there is little need for a formal sampling procedure. In many cases, however, the population is very large and conclusions regarding this population are desired using a minimum of measurements (and time and cost). Considerable time is spent discussing the need for a random sample if the Laws of Chance are to be satisfied and the reliance of the various statistical analysis procedures on the

Laws of Chance is emphasized. The definition of a random sample is that each possible outcome of an event has an equal chance of being measured. This can only be achieved by using a random number generator of some sort which covers the entire population.

One further point discussed on the Experimental Planning topic is the personal recommendation of keeping the studies simple. Many small studies concerning two or three factors are easier for the student to comprehend than trying to measure everything in one big study. Computer programs exist which can analyze large amounts of experimental data but the human mind is much more limited in trying to fully understand and document the results of these studies.

The importance of documenting and communicating the results is discussed in terms of what the student will be expected to do upon graduation. Someone can be hired at minimum wage who cannot tell the manager what the results mean in a clear manner; why pay someone engineering wages for the same lack of information. This leads naturally into a plug for the writing and speaking courses which most students dislike.

I generally spend about half the course on the topics of this section.

Analysis of the Results:

Once the data are obtained, the previously determined procedure is used for analysis. I generally spend time discussing the general features of the various common procedures with a brief worked example of one or two. Computer usage is encouraged in the planning and analysis stages if the programs are available, with an understanding of the procedure determined through a separate in-class test.

The Langley text is very good in this regard. The last half of the text contains a brief description of many common analysis procedures with the required tables and worked examples. This text was pre-computer so the mathematical manipulation is simplified. These descriptions can be used to guide the student in a project.

Project:

The experimental project is key to illustrating the important points of the course. The general ground rules are that the student states a problem which involves a one-on-one comparison, designs an appropriate experiment, and analyzes the results using a standard, preselected technique. A simple one-on-one comparison allows the student to complete the project in a reasonably short time of two to three weeks.

Topics for the comparison are selected by the student with the problem statement reviewed by the instructor prior to any data collection. The review is to insure that the problem statement is to the point and does not involve too much work. Most students greatly underestimate the amount of time involved in properly gathering data and trying to solve a problem of this nature. A discussion of the amount of generalization which can derive from the completed project based on the problem statement is included in the review. Allowing the students to choose their topics leads to many similar topics such as how many red versus green M&M's are there in a package but also leads to useful information such as which brand of popcorn gives the most old maids or which bartender at the local hangout fills the glasses the fullest. One or two times through the course will give you great insights on which local store has the best price on beer or which hunting ammunition gives the most accurate and precise patterns.

The project is documented in a formal engineering technical report and I normally grade on content, spelling, and English usage.

SUMMARY

An outline for an introductory statistics course has been presented which is designed for students who do not take a full semester statistics course. The course is designed to be taught in 10 - 16 class hours and covers topics of most use to working engineers and engineering technologists. The understanding of numerical information is presented followed by an introduction to probability and probability distributions. Considerable time is spent on the statement of the problem and designing a proper data collection method. Statistical analysis techniques are discussed and a final project using student selected topics reinforces the main points of the course.

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The above represents views based on my experience. I am very interested to hear from others as to their experiences and welcome suggestions on course improvements. Please contact me at:

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