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# The Taguchi Methods of quality control examined: with reference to Sundstrand-Sauer

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The Taguchi Methods of quality control examined:  
With reference to  
Sundstrand-Sauer

by

Cheryl Lynn Moller-Wong

A Thesis Submitted to the  
Graduate Faculty in Partial Fulfillment of the  
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Signatures have been redacted for privacy

Iowa State University  
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## TABLE OF CONTENTS

	PAGE
INTRODUCTION . . . . .	1
Why the Importance? . . . . .	1
Objectives of Research . . . . .	2
Procedure . . . . .	3
BACKGROUND PERSPECTIVES . . . . .	4
Quality Control . . . . .	4
On-line Methods . . . . .	6
Off-line Methods . . . . .	8
The Design of Experiments . . . . .	9
Who is Taguchi? . . . . .	11
THE TAGUCHI METHODS EXAMINED . . . . .	13
Quality Control . . . . .	13
Quality Engineering . . . . .	14
The Quality Loss Function . . . . .	16
Factorial Design . . . . .	20
TAGUCHI STUDY AT SUNDSTRAND-SAUER . . . . .	23
Product Description . . . . .	23
Designing the Experiment . . . . .	24
Conducting the Experiment . . . . .	26
Experimental Analysis . . . . .	26
Application of Results . . . . .	30
Use of Taguchi at Sundstrand-Sauer . . . . .	31
RESULTS . . . . .	34
Evaluation of the Results . . . . .	34
Factor G . . . . .	34
Replication of Data . . . . .	35
Normal Plotting of Estimated Effects . . . . .	36
SUMMARY AND CONCLUSIONS . . . . .	37
RECOMMENDATIONS FOR FURTHER STUDY . . . . .	40
BIBLIOGRAPHY . . . . .	42
ADDITIONAL REFERENCES . . . . .	44

## LIST OF TABLES

	PAGE
TABLE 1. Full factorial design . . . . .	22
TABLE 2. Fractional factorial design . . . . .	22
TABLE 3. Definition of factors and levels . . . . .	25
TABLE 4. Taguchi test design . . . . .	26
TABLE 5. No-neutral test results . . . . .	27
TABLE 6. Analysis of Taguchi study . . . . .	28

## LIST OF FIGURES

	PAGE
FIGURE 1a. Traditional interpretation of specifications . . . . .	18
FIGURE 1b. Taguchi interpretation of specifications . . . . .	18
FIGURE 2. Taguchi no-neutral graphs . . . . .	29

## INTRODUCTION

## Why the Importance?

The reason for this study is the increasing importance of improving product quality and reducing production costs. American companies are finding quality issues an essential part of maintaining, or regaining, a competitive manufacturing position. For many years, the quality of products produced in this country was unquestioned. The United States led the world in the quality of work produced. Prior to World War II and immediately thereafter, Japanese product quality was considered among the poorest, if not the worst, in the world [1].

But all of that has changed. The Japanese are now considered to be the world leaders in product quality [2]. Why has the United States faltered while Japan has surged ahead? Part of the answer to that question is the adoption of statistical quality control and commitment of top management to provide the proper environment for quality.

This study describes a "system" of Japanese quality control, specifically the Taguchi Methods. The Taguchi Methods are the work of Dr. Genichi Taguchi. He is a Japanese engineer who has been active in the improvement of Japan's industrial products and processes since the late 1940s. To quote one source:

Dr. Taguchi is the Japanese Messiah of efficiency whose teachings have put the Land of the Rising Sun on the top of the world [3].

It is the success of the Japanese in the arena of quality which has kindled or rekindled interest in statistical quality issues from manufacturing companies in the United States.

This thesis also examines some of the disagreement on the "true benefit" of the use of the Taguchi Methods. Since the arrival of the Taguchi Methods in America, reaction to them has ranged from unrestrained praise to public condemnation. Some individuals have called the methods one of the most important developments in decades for improving industrial productivity and quality. Others have pointed out that many of the ideas are neither new or original, and have claimed the techniques are simply outdated, recycled ideas of others.

### Objectives of Research

The objectives of this thesis are:

1. To describe what is being referred to as the Taguchi Methods.
2. To explain and analyze the statistical foundations upon which the methods depend.
3. To describe an in-plant implementation of the methods at a local industry.
4. To critically analyze and evaluate the procedures from an engineering standpoint.

5. To provide a detailed bibliography of articles and information pertaining to the Taguchi methods.

### Procedure

This research project was accomplished with the help of a local Ames plant (Sundstrand-Sauer) headquartered in Rockford, Illinois. This company had a Taguchi study in the planning stages and allowed the researcher to be involved in all phases of the project. Several plant visits were made to become familiar with the product, assembly methods and testing procedures. Additional information was gained as the Taguchi study pumps were assembled and tested. Finally, a great amount of data was gathered as the Taguchi study reached the analysis stage. A wealth of information and invaluable assistance and insights were provided by the engineer in charge of the Taguchi "no-neutral" study.

Literature (i.e., periodicals, books, manuals, etc.) on quality control, experimental design, Genichi Taguchi and the methods he advocates was reviewed and summarized. Information and articles not specifically referenced in the thesis are included in the Additional References section immediately following the Bibliography. Distinct features of the Taguchi Methods were identified and an attempt was made to clear up some of the mystery or obscurity surrounding the approach.



## BACKGROUND PERSPECTIVES

### Quality Control

Quality has been variously defined as "fitness for use", "meeting an expectation", "degree of excellence", and "conformance to a standard", along with other phrases. The American Society for Quality Control defines quality as:

totality of features and characteristics of a product or service that bear on its ability to satisfy [a user's] given needs [4].

High quality products have been around since ancient times. Inks made under controlled conditions have not faded with time. Parchments and other writing materials have not disintegrated with age. Some of the ancient metals produced (especially bronzes) are thought to be of a higher quality than similar metals made today. The condition of the cloth wrapping mummies, some dating back as far as 1000 B.C., is another example of the excellent quality of products from our remote past [5].

Early requirements for quality are found in the products of China and other parts of Asia as well as Europe. Improvements based on successes and failures were continually being made. However, no definite methodology for improvement was in effect. Because of a great lag in methods of transportation and communication, it often took

years for a nation or region to reap the benefits of discoveries made in other areas of the world.

Improvements in communications become a significant factor in providing more rapid improvements in technology and the production of quality products. The development of railroads to replace the horse-drawn wagons and carriages was also a great step forward. Before the nineteenth and twentieth centuries, technological advances occurred rather slowly. As innovations such as telephones, diesel locomotives, air travel and automobiles were introduced, a chain-reaction of sorts led to many new ideas, materials, processes and inventions.

In early times, a craftsman was the sole person responsible for the quality of product produced. Rules were established for apprentices to become masters of their trade, and quality standards for finished products were set. These rules and standards were closely followed especially in the tapestry and ceramic making trades.

The concept of specialization of labor came about during the Industrial Revolution. With this concept, a worker was no longer responsible for making the whole product, but for only a part of it. This led to organizing workers into groups and making the group supervisor responsible for the quality of the output. As products

became more complex it became necessary to examine workers' output using full-time inspectors.

There was a great need for more accuracy and precision during this period of industrial growth. New methods, processes and machinery warranted more accurate measurement and dimensional control.

Quality control can be divided into two main activities: on-line and off-line methods. Off-line refers to the activities in the design phase of development before the product is released to manufacturing. On-line quality control relates to the activities that occur on the manufacturing line.

#### On-line Methods

A review of the literature indicates that on-line quality control methods began in 1916, when C. N. Frazee of Bell Telephone Laboratories developed the operating characteristic (OC) curve for inspection problems. It was then necessary to have measures of the probability of acceptance for various sampling plans in popular use. The curves and tables developed for this purpose by Thorndike and Molina are still used today in sampling inspection and reliability engineering.

Several years later, a development which was considered to be a major milestone in the area of statistical quality control was made. W. A. Shewhart working at Bell Telephone Laboratories developed control charts to evaluate whether a process was controlled within chance variation limits or was out of control due to some definite, assignable causes. Dr. Shewhart continued his studies of statistical applications in the inspection department of the Bell Telephone Laboratories. He was joined by H. F. Dodge, G. D. Edwards and H. G. Roming and the December 1944 issue of Fortune magazine listed these men as the original developers of the quality control movement.

The concept of acceptance sampling was first published by H. G. Roming in 1939. More statistical methods were used at Bell Labs throughout the thirties and forties, however, the application of statistics to quality control problems was not well received by industry until World War II.

The American Society for Quality Control was established in 1946, and has played an important role in the development and support of the quality control discipline.

### Off-line Methods

The off-line methods of quality control are newer than the on-line techniques. The literature indicates that it was not until the early 1950s that reliability and other off-line methods were recognized for their applicability to quality control.

In the early 1950s the Department of Defense and the electronics industry commissioned a task force called the Advisory Group on Reliability of Electronic Equipment (AGREE). The AGREE report recommended that a special discipline be imposed during the development phases to ensure that designs would be reliable. To be included in the discipline was design analysis techniques and formal reliability demonstration testing.

Recent developments in reliability have tended to reduce the emphasis on predicting and demonstrating reliability. More emphasis is being placed on design analysis and on testing to discover potential weaknesses so that improvements could be made early in the development cycle. This approach has long been used by the best of the commercial industries, and the purchasers and developers of large systems [6].

In addition to reliability studies, the off-line quality control methods common in the U.S. include

maintainability, sensitivity analysis, and prototype testing. Maintainability is concerned with implementing principles basic to future equipment repair while the equipment is being designed, developed, or fabricated. Sensitivity analysis deals with making products robust to operating and environmental variation. Prototype testing is done to insure optimum design, layout, operation, and/or safety.

### The Design of Experiments

History indicates that the study of experimental methods was begun during the eighteenth and nineteenth centuries in agricultural field experimentation [7]. Much of the initial work took place at the Rothamsted Experiment Station in England.

It was in 1926 that R. A. Fisher wrote a paper entitled "Complex experimentation" in which he first made mention of what we now call factorial experimental design. This technique was described in more detail in another of Fisher's works, the "The Design of Experiments" [8].

The notion of how to logically choose an experimental subset of exorbitantly large combinations of influential factors was first offered by F. Yates in "Complex Experiments" [9], which came to be the cornerstone of comparative experimentation.

Next, in his paper dealing with the confounding in factorial experiments with relation to groups [10], Fisher introduced the idea of treatment-block combinations for factors with a prime number of levels.

W. G. Cochran joined Fisher and Yates at Rothamsted in 1936. Further development of experimental design theory culminated in Cochran's "The analysis of lattice and triple lattice experiments in corn varietal tests" [11] which for many years was the only working manual for agricultural experimenters wishing to use the new experimental design ideas.

More refinements in the design area came ten years later with "Experimental Designs" [12] where Cochran and Cox were able to describe in some detail the most useful of the designs that had been developed up to that time. The book was directed at the experimenter and was intended to serve as a handbook to be consulted when a new experiment was under consideration. Over the next six years, the growth in the number of experimental designs required the authors to include an index of the hundreds of designs that they were unable to include in the second edition of the book.

Review of the literature has shown that much was known and published about experimental design theory prior to the development of the Taguchi Methods in Japan by Dr. Taguchi in the late 1940s.

Historically, experimental design techniques have not been a part of the education of American engineers. Engineers tend to face roadblocks with conventional experimental design because there is no way to work with the large number of variables, interactions, and levels of variables present in an industrial setting without the appropriate training.

#### Who is Taguchi?

Dr. Genichi Taguchi is a Japanese engineer who in 1949 and the years following developed and introduced his techniques of experimental design. Taguchi's techniques, called the Taguchi Methods, are both a philosophy and methodology for quality improvement that depends heavily upon statistical tools and concepts, especially the statistical design of experiments.

Dr. Taguchi, working in the Electrical Communications Laboratories (ECL) in Japan after World War II, was assigned the task of promoting research and development productivity for ECL. It was in this setting that Taguchi developed the methods used today. Taguchi is a successful author in Japan and has been the recipient of the Deming Prize on several occasions for his contributions to statistical quality control.



Dr. Taguchi has given seminars in the United States since the early 1970s, but it wasn't until about 1980 that American companies began actively applying his ideas. The Center for Taguchi Methods at the American Supplier Institute, Inc. in Romulus, Michigan is the current connection for U.S. companies seeking information on the Taguchi methods.

Taguchi has been credited with bringing experimental design to the forefront of product and process design and improvement. His success in arousing interest must be weighed against the benefits realized by the approach.

## THE TAGUCHI METHODS EXAMINED

## Quality Control

As discussed in an earlier section, the two main quality control activities are on-line and off-line methods.

Traditional quality control methods such as control charts and acceptance sampling are used during the manufacturing process. These on-line quality methods are conducted to keep the manufacturing process in statistical control and to reduce product imperfections.

Taguchi claims to recognize and support on-line quality control; however, he says there are substantial differences between his on-line quality control methods and the current "Western" techniques. This on-line portion of the Taguchi methods is related to the operations research area. For purposes of this thesis, it is considered to be outside the realm of investigation.

The emphasis in this thesis, and the Taguchi area receiving the most press, is another aspect of quality control, the off-line techniques. Off-line quality control methods common in the U.S. are sensitivity analysis, prototype tests, and reliability studies.

## Quality Engineering

Manufacturers of high quality products use off-line quality control to improve product manufacturability and reliability and to reduce product development costs.

Taguchi's main emphasis is in the area of off-line quality control. His approach is called "quality engineering". It involves engineering and statistical methods to achieve improvements in cost and quality by optimizing product and manufacturing process design.

The off-line Taguchi methods are employed in two ways. One area is as an engineering tool during the research and development processes prior to production of a product. The other area of use is in the optimizing of existing product and process performance. Both areas of application depend upon the statistical design of experiments.

Off-line quality control involves finding a good system configuration to perform the function intended in the product. If in the engineering phase of the development process, it is realized that the system is no longer applicable, Taguchi says "it's back to the drawing boards" to find the right system.

Taguchi also has two types of active engineering designs beyond the selection of the system. One of the approaches is to find the levels of the parameters that will

introduce the least variation into the product, process or service. The second approach is to determine which of the factors contribute most to the end product's variation thus indicating which tolerances to tighten and which to ease. In particular, the Taguchi Method outlines a three-step approach for engineering quality into a product:

- system design
- parameter design
- tolerance design

System design is applying engineering and scientific knowledge to product and prototype design. The prototype defines the initial settings of product or process design characteristics.

The central theme of parameter design is to reduce costs by reducing variability. A product or process can perform its intended function at many settings of its design characteristics but some may give more uniform service than others. Topics included in the area of parameter design are minimizing variation by making products robust to environmental and component variation.

Tolerance design is a method for specifying the tolerances that minimize the costs associated with manufacturing. Taguchi emphasizes that tolerances can be assigned scientifically rather than by engineering convention.

Taguchi advocates the use of the three design steps in the order presented above to optimize cost, quality, and productivity.

### The Quality Loss Function

The use of the quality loss functions has been popularized by Taguchi. The basis of this philosophy is that economic loss can be reduced by continually reducing the variability in the process and expressing the loss associated with this variability in terms of money. The loss function is the loss that occurs when the process is not capable of producing a product exactly meeting the target value for a performance characteristic of the manufacturing process.

Dr. Taguchi has said:

The quality of a product is the [minimum] loss imparted by the product to the society from the time the product is shipped [13].

Taguchi views the "loss to society" in a very broad sense. He associates loss with every product that among other things include consumers' dissatisfaction, added warranty cost to the producer, and loss due to a company having a bad reputation and losing a market share.

From an engineering standpoint, the losses of concern are those caused by a product's functional characteristic

deviating from its desired target value. To minimize loss, a product must be produced at optimal levels and with minimal variation in its functional characteristics. A comparison of the traditional specification methods and the Taguchi method are shown in Figure 1. The second figure shows that the loss when the target is met is zero. As the performance moves away from the target, the loss to society increases at an increasing rate.

Taguchi suggests defining the function shown in Figure 1b in terms of the following equation:

$$\text{Loss}(y) = k(y - m)^2$$

where

$$k = A/(d^2)$$

and

- A = the cost of corrective action necessary to change the process
- d = the value of the process
- m = the target value of the process characteristic
- y = the measurement of the unit in question
- k = the loss coefficient
- Loss(y) = the incremental loss

There is a lot of information about the quality loss function in the literature and courses taught through the American Supplier Institute. However, no direct link exists between quality loss functions and experimental design. In

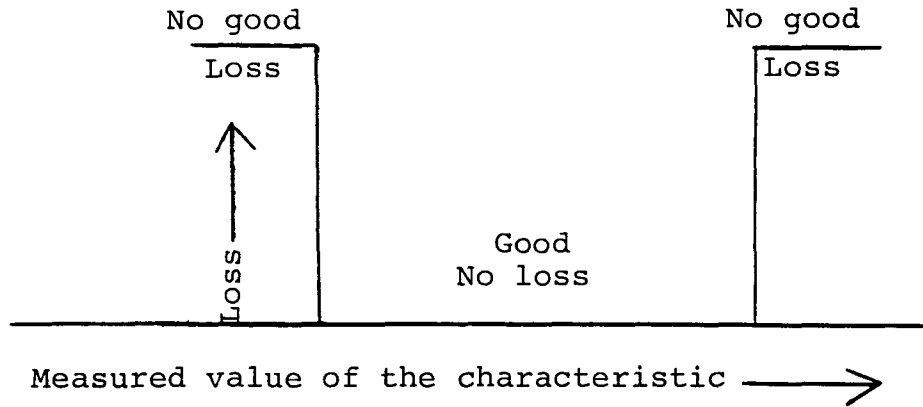


FIGURE 1a. Traditional interpretation of specifications

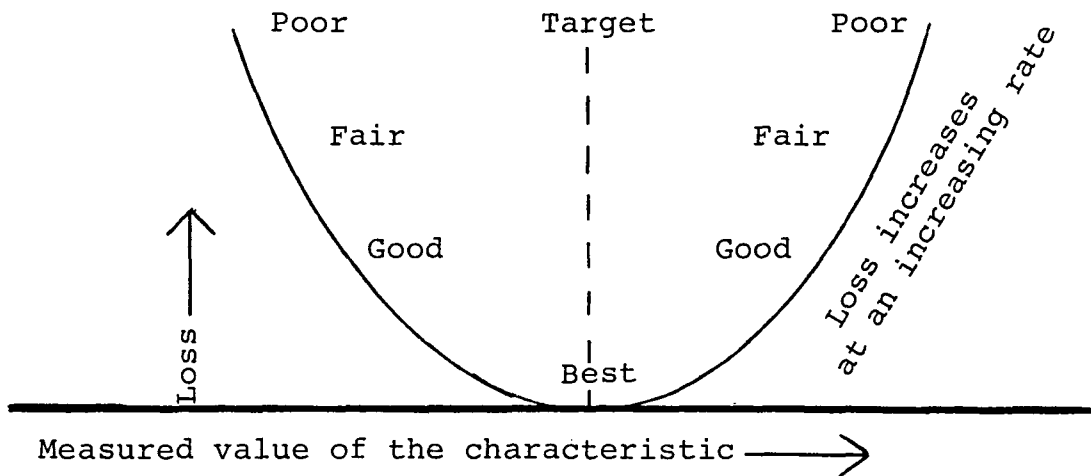


FIGURE 1b. Taguchi interpretation of specifications

industrial application studies, the entire focus is on designing experiments not computing a loss function. This idea seems to be disjoint with the balance of the Taguchi methods, especially as used in an industrial setting.

The factors which affect the product's functional characteristics are of two types: controllable factors and noise (or uncontrollable) factors.

Controllable factors are those which can easily be held at a desired level such as choice of material or cycle time. Noise factors on the other hand, are those nuisance variables which are either difficult, impossible or expensive to control.

Taguchi defines three types of noise factors: "outer noise", "inner noise" and "between product noise". Ambient temperature, humidity and human error may be considered to be outer noise, the aging of the machinery and tolerances on the process factors may be inner noise, and manufacturing imperfections are responsible for the between product noise.

After making a clear distinction between all sources of noise and a strong case for product and process robustness, Taguchi has failed to follow-up on these ideas in his experimental design strategy. The lack of any replication of designs and the use of fractional factorials makes it impossible to determine the source of the noise and few conclusions about the robustness can be made.



## Factorial Design

The factorial experimentation suggested by Fisher [14], is a major contribution to the experimental sciences. Perhaps the most obvious experimental strategy is to run a separate experiment for each factor, having as many experiments as there are factors. Factorial design offers an alternative. When factors can be studied simultaneously in a single experiment, a more economical use of resources can be made and appropriate data for investigating the interrelationships among the effects of factors will be provided.

Although factorial experimentation is a major contribution to the experimental sciences, there are limitations on its utility. The most obvious is that factorial experiments become prohibitively large if the factors are numerous. If a complete factorial experiment is too large, and the experimenter is unwilling to decrease the number of factors or the number of levels of each factor, he or she must then accept some sacrifice in the quality of information obtained in order to reduce the size of the experiment. There is both good empirical evidence and theoretical reasons to expect that not all of the information provided by a full factorial study is needed to identify the important effects.

Fractional factorials allow the experimenter to identify the important effects without running every one of the possible combinations of the full factorial design. One must be clever in both the choice of some of the full factorial combinations and the means of data analysis to be able to identify the vital effects.

Fractional factorial designs offer a great deal of convenience because of their size. Ideally, the results of one experiment will direct the choice of factors in succeeding experiments, thus being the building blocks of sequential experimentation.

The basic principles of fractional factorial designs can be illustrated by considering an experiment which contains three factors, A, B, and C. Each factor is to be investigated at only two levels, say high (+) and low(-). A full factorial would warrant the design shown in Table 1, where there are eight possible combinations of the three factors. A good half fraction design is demonstrated in Table 2.

If one considers the full factorial in Table 1, it can be noted that the effects break into columnar pairs which have opposite sign combinations. Analysis of the half fraction of the  $2^3$  design in Table 2 shows that it consists of "all high" combinations.

TABLE 1. Full factorial design

FACTOR								
A	-	+	-	+	-	+	-	+
B	-	-	+	+	-	-	+	+
C	-	-	-	-	+	+	+	+

TABLE 2. Fractional factorial design

FACTOR				
A	-	+	-	+
B	-	-	+	+
C	+	-	-	+

Taguchi's approach to the use of fractional factorials has been to present several design plans, denoted as L8, L16, L27, etc. The most common design used by Taguchi-influenced engineers tends to be the L8 design with large differences between factor levels. The experimental strategy Taguchi employs is a one-shot screening with the intent of catching gross effects. Many quick studies are used to improve a variety of product or process designs.

With Taguchi's approach; however, the tendency is to overlook the important fine-tuning required by many processes and leave unanswered some of the ambiguities resulting from the initial fractional factorial experiment.

## TAGUCHI STUDY AT SUNDSTRAND-SAUER

## Product Description

A Taguchi study was conducted at the Sundstrand-Sauer plant in Ames, Iowa between May and November, 1987. The study involved a recurring adjustment problem on the medium duty products line.

The product under study was a tandem pump with a variety of construction and farm equipment applications. The pump is generally sold in conjunction with a variable displacement motor which together serve to drive the wheels or other parts of heavy machinery. The primary users of the products are manufacturers of large tractors, trucks and off-road vehicles.

The adjustment of the product involved the positioning or centering of a spring sub-assembly and/or adjustment of the rotary spool control valve. When the pump is in proper adjustment and oil pressurized to 500 pounds per square inch (psi), it will return to a zero pressure or neutral position. It was from this characteristic that the project became known as the "no-neutral" Taguchi study. The acceptable specification range for this adjustment is 200 psi.

The problem occurred when sixty percent of the products on a particular build were not adjustable to within the specification limits. There was no indication of differences in parts or assembly methods. The parts that were unadjustable were taken apart, reassembled, then readjusted. The majority of the rebuilds were brought into adjustment, but there remained six pumps that were still outside acceptable specification limits.

Because of a lack of assignable causes for the adjustment problems encountered in that particular build, the quality control personnel at the plant felt that there was a great possibility of the problem reoccurring.

#### Designing the Experiment

The process began with a brainstorming session involving those associated with the design, build, and test functions of the product. Over 50 possible factors were suggested. This number was reduced to seven through the process of elimination. (The choice of seven factors was based upon precedence. This type of seven-factor, two-level experimental design had been used for other Taguchi studies at this plant.)

The test factors could be classified in two major areas:

- hardware(internal to the product)

- testing(test routine or internal to the test stand)

The variables to be measured were the time it took to bring the product into adjustment, and how close to zero (neutral pressure) the pump was able to return to after pressurizing to 500 psi.

The factors and levels of the experiment were defined as shown in Table 3.

TABLE 3. Definition of factors and levels

Factors	Level 1	Level 2
A) Journal bearing thickness difference	0.000"	0.004"
B) Servo bore/piston clearance	0.012"	0.020"
C) Rear cover alignment	centered	turned CCW
D) Cradle fit	0.002"	0.006"
E) Servo spring squareness	1 degree	3 degree
F) Test circuit	rear	front
G) Servo gage loop	with	without

The first five of the factors (A-E) were hardware related, the last two (F-G) were test related. The Level 1 (low) was generally the present specification or method of assembly or test employed at the time of the study. Level 2 (high) was chosen using engineering judgment or as the only alternative to Level 1.

### Conducting the Experiment

The factors (A-G) and levels (1-2) chosen were arranged as shown in Table 4. This experimental design requires that eight pumps be built and tested. Taguchi has called an orthogonal array like this a  $L_8(2^7)$  design.

TABLE 4. Taguchi test design

FACTOR	A	B	C	D	E	F	G
Test #1	1	1	1	1	1	1	1
Test #2	1	1	1	2	2	2	2
Test #3	1	2	2	1	1	2	2
Test #4	1	2	2	2	2	1	1
Test #5	2	1	2	1	2	1	2
Test #6	2	1	2	2	1	2	1
Test #7	2	2	1	1	2	2	1
Test #8	2	2	1	2	1	1	2

After each of the eight parts were built, they were tested to determine the amount of time it took to adjust the product and to record how the tandem pump performed under different test conditions.

### Experimental Analysis

The results showed the average time to bring the part into adjustment to be 1.27 minutes. This measure was felt

not to be of significance and all further evaluation of the results concentrated on the performance of the pump after pressurization.

The pump was tested by pressurizing to 500 psi and allowing it to return to as near zero (neutral pressure) as possible. Results of this portion of the test ranged in value from 37 to 449 psi. The complete results of the oil pressurization test are shown in Table 5.

TABLE 5. No-neutral test results

TEST	TIME TO ADJUST	FORWARD 500 psi	REVERSE 500 psi	RANGE 500 psi
#1	1.00	+ 88	-171	259
#2	2.05	+246	- 1	247
#3	1.13	+100	-153	253
#4	1.10	+190	-259	449
#5	1.32	+424	- 1	425
#6	1.23	+ 1	- 36	37
#7	1.53	+103	-263	366
#8	0.37	+ 69	- 49	118

The next step in evaluating the results involved finding the average value from each factor at each level. This was achieved by combining the factor and level information from Table 4 and the range values in Table 5 to calculate the average range values. This information is summarized in Table 6.



TABLE 6. Analysis of Taguchi study

FACTOR	LEVEL	--TEST NUMBERS--				RANGE
A	1	1	2	3	4	302
	2	5	6	7	8	237
B	1	1	2	5	6	242
	2	3	4	7	8	297
C	1	1	2	7	8	248
	2	3	4	5	6	291
D	1	1	3	5	7	326
	2	2	4	6	8	213
E	1	1	3	6	8	167
	2	2	4	5	7	372
F	1	1	4	5	8	313
	2	2	3	6	7	226
G	1	1	4	6	7	-a
	2	2	3	5	8	-a

<sup>a</sup> This factor of the test was incorrectly performed, therefore it was ignored in later analysis by Sundstrand-Sauer.

As noted in Table 6, one of the seven factors (the servo gage loop) was eliminated from the remainder of the study due to errors made when performing the tests.

Once the average range value for each factor at each level was determined, these values were graphed. Although no additional information is gained, the graphing of the data in Table 6 allows for a visual impression of the variation in the data (See Figure 2).

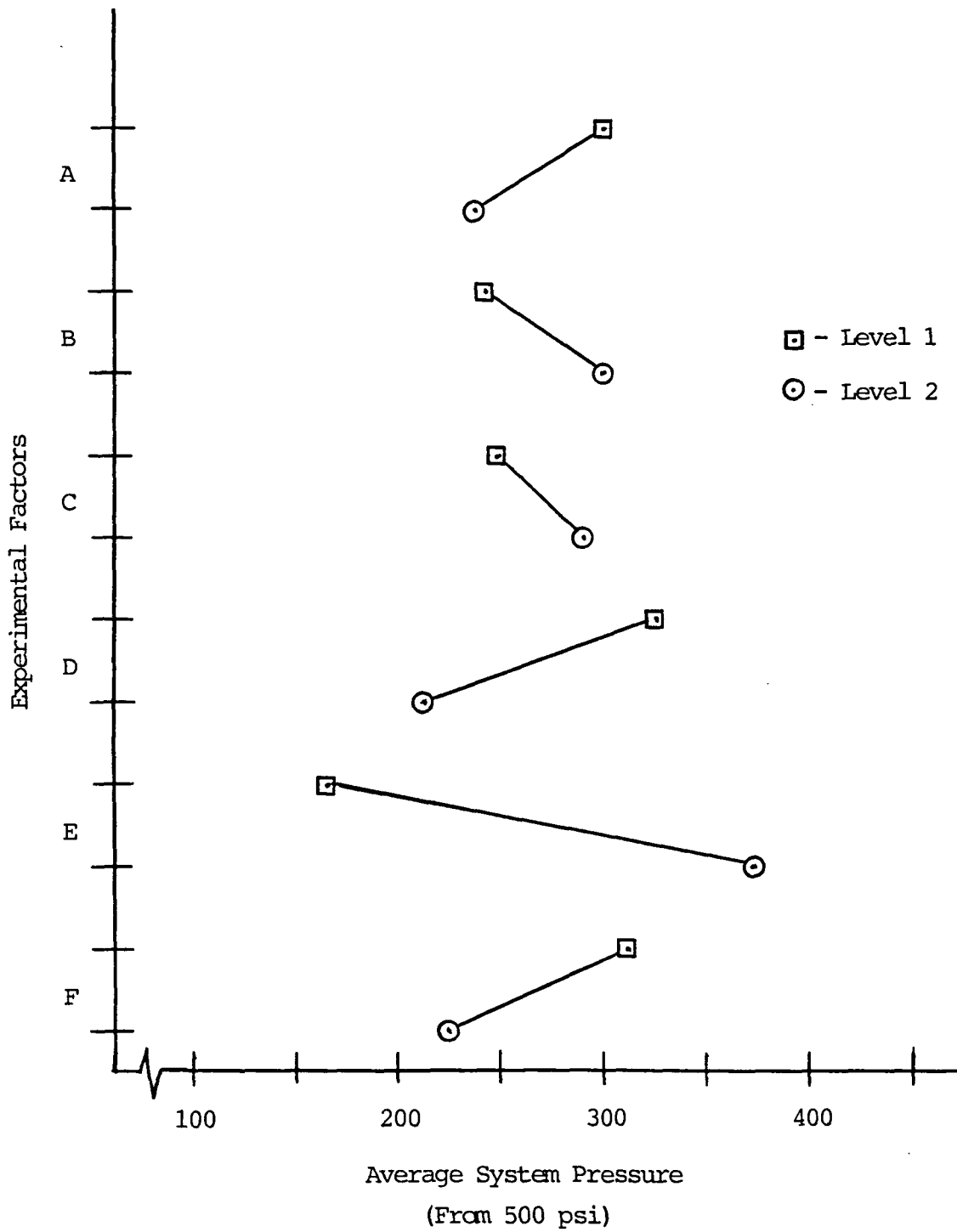


FIGURE 2. Taguchi no-neutral graphs

The remaining six factors when graphed, indicate that the most critical factor was the servo spring squareness (Factor E), the second most critical factor was the cradle fit (Factor D).

A summary of the information that Sundstrand-Sauer felt was gained by doing this experiment is given below:

- Factors A,D and F tended to perform better at Level 2.
- Factors B,C and E tended to perform better at Level 1.
- Additional testing suggested by this experiment could lead to more improvements in the product.

#### Application of Results

Design changes to the tandem pump, as suggested by the experiment were investigated and applied where possible. Caution was used to be certain that one particular change did not interfere with the performance of a different aspect of the operation of the pump. For example, the servo bore/piston (factor B) performed best with low clearance. But that clearance cannot be made too small because of the necessity of space for oil to flow for lubrication purposes.

A follow-up test was run after all changes suggested by the Taguchi experiment had been made. In this confirmation

study of twenty tandem pumps, the average range difference was found to be 70 psi. The engineer in charge of the study felt that the test and subsequent changes made had been successful in lowering the range of oil pressurization values obtained during the adjustment of this product.

No additional Taguchi studies are planned for the tandem pump at this time.

#### Use of Taguchi at Sundstrand-Sauer

The use of the Taguchi methods at Sundstrand-Sauer began in early 1986 when one person from the Ames plant attended a three day Taguchi workshop sponsored by the American Supplier Institute. Upon his return, he conducted a series of two day classes similar to those he attended for in plant personnel. The classes were each comprised of about twelve people including engineers, supervisors, and other manufacturing personnel. It is estimated that twenty-five persons have attended the classes, but that only eight or ten people are actively involved in using the methods at the present time.

As a part of the class, each person was required to set up and run a Taguchi study in their work area. From this requirement, several of the initial studies performed at the Ames plant were conceived.

It is estimated that between fifteen and twenty Taguchi studies have been conducted during the past year. All of the studies have consisted of either four or seven factor experimental designs.

For comparison purposes, the study described in this thesis was considered to be a medium-sized experiment. There was one larger Taguchi experiment conducted at the plant. And although the number of factors was seven in this larger experiment, it took much longer to collect the necessary parts, to schedule the build, and to analyze the results.

A demonstration of the lack of success in identifying a main effect through the use of the Taguchi methods was described with regard to a customer service problem. The experimental design called for several levels of experienced operators to use the equipment and report on the "feel" and amount of response under several test conditions. The analysis of the responses offered no additional information and another method (customer surveys) was necessary to obtain the required information.

The overall success rate of the Taguchi experiments conducted at Sundstrand-Sauer is internally felt to be high. The methods are often used as a tool to confirm or deny suspicions about what may be happening during operation of

the part. Plant personnel are generally of the opinion that any information, which had been previously untested, is important to know. The idea that the results of one experiment may lead to more questions, and thus more experiments is viewed as a bonus of the Taguchi methods.

In a discussion with the quality assurance/reliability manager [15], he stated that the methods would continue to be used until someone can develop a more effective and equally simple approach to experimental design.

## RESULTS

### Evaluation of the Results

To evaluate the results of this study, two contributing elements must first be explored. First, one must make a evaluation of the statistical error introduced when one of the seven factors (Factor G) was incorrectly tested and later removed from all further analysis. Second, one must evaluate the validity of the results considering that there was no replication of data in the test design.

#### Factor G

A major shortcoming of the study performed at Sundstrand-Sauer was the problem encountered with Factor G. The test of the servo gage loop was designed to test whether or not having the loop connected during testing made a difference in the oil pressurization range found during the adjustment of the pump. The Taguchi design was not followed in this respect, and was therefore ignored in the analysis phase of the project by the engineer in charge of the study at Sundstrand-Sauer.

It is felt that this error introduced an additional bias to the results. When determining assignable causes, this factor may or may not have been as crucial as any of the other results found.

Instead of ignoring the gage loop factor, it is felt that additional time and expense would have been well spent in completing the experiment as designed. Lacking the ability to retest the pumps, linear regression was used to generate a probable pressurization range for Factor G. This multiple linear regression was performed using the Statistical Analysis Software (SAS) package on the NAS AS/9160 computer at ISU [16].

The result of the regression analysis showed a range value of less than that of Factor E; however there was a high correlation between Factors E and G ( $r = 0.71$ ).

#### Replication of Data

In the study performed at Sundstrand-Sauer, as in other Taguchi studies in general, there was no replication of tests. Replication is defined as a complete repeat of the experimental run, it is used to evaluate the size of experimental error [17]. Replication is an important concept in all testing environments, as it allows for the evaluation of between product variation and testing noise. The data and results found in the Taguchi experiment lack any measure of the permanent and inseparable variations from pump to pump. Without the measure of this inherent variation between pumps, it is impossible to determine if the results are truly significant.



### Normal Plotting of Estimated Effects

As an additional evaluation of the results, a normal plot of the estimated effects for the data found in the Taguchi study was performed.

This technique, as suggested by Box, Hunter, and Hunter [18], is a useful method in the evaluation of data from two-level fractional factorial experiments especially when there is no replication, as in the majority of the Taguchi studies.

A graphical way to identify estimated effects that are not explainable solely in terms of random variation is to look for departures from linearity on a probability plot of estimated effects.

Using Yates algorithm and plotting techniques suggested by Daniel [19], and Box, Hunter, and Hunter [20], one may expect that when normal plotted, a nearly linear result can be judged to carry no vital information.

An interactive computer program [21] which identifies statistically detectable effects via normal plots and half-normal plots as described previously, was used to evaluate the Taguchi study performed at Sundstrand-Sauer.

The results indicate that there were no large or "active" effects in the study. The normal plot of the data was very near linear, therefore nothing more than random variation is indicated.

## SUMMARY AND CONCLUSIONS

Emergence of the Japanese methods of quality control in the U.S. began because of the success demonstrated by industrial corporations in Japan. In order to maintain or regain an edge in international markets, American companies are actively pursuing an optimum quality formula. Many companies are willing to try any "new" approach in the hope of finding a better way to do things.

The Taguchi methods covered in this thesis were the specific topics dealing with off-line methods of quality control. Taguchi also has published methods of on-line quality control, but they have certainly not received the attention or high acclaim that his off-line methods have.

The concept of quality loss functions, although emphasized in the Taguchi literature, is no more than defining a monetary value to associate with potential savings. It does not influence or change the main focus of the the Taguchi methods which is the design of experiments.

The Taguchi methods offer a cookbook style approach to experimental design that is attractive to some U.S. industries out of the desire for simplicity. There are many published reports on the successes of the Taguchi methods as demonstrated by the millions of dollars saved by proponents of the methods.

Examination of the underlying principles of the Taguchi methods found many similarities to statistical and managerial techniques which had been developed but used sparingly for many years in the U.S. and other countries.

Taguchi can be credited with bringing the idea experimental design to the forefront of current product and process design study. Taguchi cannot; however, be credited with inventing an entirely new area of quality control.

The study at Sundstrand-Sauer served as a model of a typical methods application in American industry. The training for the plant personnel responsible for conducting the study at Sundstrand-Sauer did not involve understanding the underlying statistical implications or details relating to the methods. When errors were made during the testing process, the engineer in charge was not concerned with the bias introduced by choosing to ignore one of the seven factors in all further analysis of the experiment.

Based on the information contained in this thesis, these additional conclusions are drawn:

- Several of Taguchi's ideas are not congruent with the experimental means provided by his cookbook style approach to fractional factorial design.
- Although the quality loss function is covered in some detail in the Taguchi methods, it is not used in association with the experimental design studies conducted in an industrial setting.
- The Taguchi methods, and the application of them, are a source of disagreement between statisticians and industry.

- There is mention of the Taguchi methods in new books and journal articles which deal with quality issues.

In summary, it is the author's personal opinion that the Taguchi methods will continue to receive attention and be a popular topic for academic and industrial investigation for some time to come. But, just as other popular topics, the Taguchi methods will eventually settle into proper perspective along with the rest of the topics which have, at one time or another, been in the spotlight.

## RECOMMENDATIONS FOR FURTHER STUDY

Areas with potential for further research are identified in this section.

The Taguchi methods covered in this thesis dealt specifically with off-line techniques. It would be beneficial to examine Taguchi's on-line methods of quality control in comparison to standard U.S. methods of control charting, acceptance sampling, etc. It would be of interest to determine how and why many U.S. companies have chosen to apply only the off-line Taguchi methods, while continuing to support and utilize all of the standard "Western" on-line quality control techniques.

It would be useful to conduct a further investigation of the type undertaken at Sundstrand-Sauer. Additional investments in time and resources would provide an opportunity to more accurately measure the success of the Taguchi methods. More time and money would be necessary to replicate the experimentally designed build and test the pumps. This; however, would be the only way to get a measure of statistical significance of the resultant data.

An ideal study of the "true benefits" of the Taguchi methods would be a comparison of the approach to experimental design and the value of the results obtainable for two separate groups. One of these groups would be

schooled in the Taguchi methods, the other would use a statistical approach to experimental design. In this type of study, an evaluation could be made of not only the effectiveness of the Taguchi methods group in identifying main effects as opposed to the statistically based group, but also of the ability of persons trained in one of the two methods to design the experiment, analyze the data, and interpret the results appropriately.

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