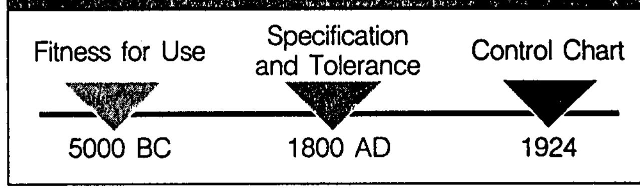
Variation Through the Ages

Man has shaped variation from fitness for use to specification and tolerance to control charts.

by Lloyd P. Provost and Clifford L. Norman

VARIATION HAS BEEN WITH us since the beginning of time, and man has reacted to it in a variety of ways. Early man dealt with variation in the raw materials he selected for tools and weapons. Modern man continues to be plagued with variation problems from raw materials to finished products. The complexity of assembled products and the demands of the information age make the problems of variation even more pronounced. No matter what improvements are made, there will always be some level of variation. In particular, understanding and managing variation in people will be an important issue for the future. Figure 1 shows the three basic inspection methods used to manage variation through the ages.

Figure 1. Methods to Manage Variation



Ancient variation

Early man experienced and accepted variation as a way of life. He knew that nature would control the quality of raw materials. A million years ago, man produced crude tools from stones to survive. Adapting raw materials to meet his needs was man's way of controlling variation. Most of the time he was the supplier, producer, and consumer of his labors.

About 5,000 years ago, the Egyptians entertained the idea of interchangeable bows and arrows. This was probably the first time the problem of variation confronted man directly. He had to deal with the differences in raw materials, craftsmen, methods, and tools. If the arrowheads he produced were much different, he would start over or rework them until the variation suited his needs. In fact, because of the simplicity of the products, variation was not a critical issue. During this early time man did not inspect to a design or specification, but inspected and worked the crafted item until it was fit for his use.

The Egyptians made extensive use of measurement. They built temples and the great pyramids, and they used measurement to help them manage their environment. Building pyramids required the guidance of priest-architects, who were accomplished mathematicians. They used their knowledge to give instructions to stone masons for cutting, shaping, and placing the stones in the great pyramids. Joseph M. Juran gives an account of how the Tomb of Meketre (about 1800 B.C.) depicts the use of measurement and inspectors.[1]

Construction was not the only use of measurement by the ancients. According to Will Durant, Egyptian life depended on the depth variation of the Nile River.[2] This led the Egyptians to observe the rise and recession of the river, to record and calculate the data, and to predict the days the Nile would rise.

Clearly, the ancients encountered variation in all facets of life. The structure and organization of ancient civilization facilitated the fitness for use concept. The fitness criterion for production meant that:

- craftsmen and consumers had direct communication.
- craftsmen enjoyed control over design and production.
- products were not complex.
- trade and commerce were local or regional.

These conditions made it possible for the fitness for use concept to survive well into the 19th century. Beginning in the late 17th century and continuing into the 20th, all of these conditions would change.

Middle Ages and the craftsman

The early craftsmen were subject to extreme variation in the source and availability of raw materials. Variation in raw materials and their crude tools required skilled craftsmen to minimize variation in the final outcome of the process. During the Middle Ages, craft guilds emerged to ensure that craftsmen were adequately trained to do just that. This system included the use of masters, journeymen, and apprentices. It was the job of the master to see that all under his direction were trained in appropriate techniques. The master also purchased raw materials, determined wages, regulated the production process, and set quality standards. In short, the master did his best to minimize the variation in the craft process. The craftsman worked the final output until it met its intended function or satisfied the master.

Technology also contributed to reduction in variation. In about 1600, England suffered a severe shortage of timber due to the use of wood for fuel in the emerging glass industry.[3] Other materials could not be used because they produced impurities in the blown glass. An alternative fuel had to be found to support the glass industry. The result was an improved process of heating glass with coal. Coal by itself produced impurities that were unacceptable, but coal used with a reverberatory furnace reduced the variation in impurities in the glass. The invention provided an alternative fuel source for making glass and reduced the variation of impurities in the final glass product to the level of those made with the scarce wood fuel.

During these early periods, each product would be examined against its intended use and accepted or rejected based on this analysis. Fitness for use was still the primary criterion for managing variation.

Interchangeability of parts

The concept of interchangeability has produced more than its share of myths. Americans are generally surprised to learn that Eli Whitney did not invent it. Others are surprised to learn that several decades of improvement in manufacturing processes and standards were necessary before interchangeability became a reality. By some measures, it was not achieved until the late 1800s.

During the middle of the 18th century, a French gunsmith, Honoré Le Blanc, developed a system for manufacturing muskets to a standard pattern.[4] This system allowed armories around the world to turn out large numbers of muskets with the added benefit of interchangeable parts. Thomas Jefferson, ambassador to France, was taken with Le Blanc's idea and tried to persuade him to go to America. Failing to do so, Jefferson tried to persuade the secretary of war and the U.S. Congress to bring the new system to America and enlisted George Washington in his efforts.

In 1798, acting on Le Blanc's ideas, the government awarded Eli Whitney a contract to supply 10,000 muskets to the government in two years. The contract was astonishing to those who procured arms; previously, two national armories had produced only 1,000 muskets in three years. Whitney designed special machine tools and trained unskilled workmen to make parts to a particular design. He then measured and compared them to a model. The sum of the parts was a musket, but any single manufactured part would fit any musket of that design exactly—in theory.

The innovation of interchangeable parts introduced a new set of problems. It took more than 10 years to deliver the first 10,000 muskets. Problems with variation in materials, tools, and workmen plagued Whitney to the point of financial ruin. Fortunately, the government permitted a schedule overrun (this was the beginning of a new tradition for many in the U.S. military-industrial relationship).

In January 1801, Whitney silenced most of his critics with a demonstration to President-Elect Thomas Jefferson and others.[5] From a pile of manufactured parts, he assembled a complete musket and proved the benefits of interchangeable parts. Whitney accomplished this feat by interchanging the assembled locks (firing mechanisms) with the other pieces of the musket. He was careful to avoid the issue of interchangeable lock pieces, an invention he had not yet achieved. Whitney's demonstration provided a vision of the power of mass production to those present and won continued support for his efforts in the form of increased schedules and money.

Interchangeability would continue to be an elusive goal for the industry. For most companies that reported success in the application of interchangeable parts, the file or rasp was the most commonly used tool in the shop. By many accounts, full interchangeability of parts was not achieved until the late 19th century in the manufacture of sewing machines.

Inspection to gaging, specification, and tolerance

The age of the craftsman did not require the use of specification because the craftsman was in direct communication with the customer. He understood the customer's needs, and it was up to him to provide a product that would match them.

The use of gages, fixtures, and other tools to deal with variation can be traced back to the work of the American armories of the 19th century. The armories during these early years depended on a system of inspection that was very subjective. The inspector would disassemble the lock to ensure that the pieces had good workmanship. The inspector would then reassemble the lock and test for function. If the musket could fire properly, it was stamped and accepted.

This system of acceptance changed in about 1819 at the Springfield Armory under the guidance of Superintendent Roswell Lee.[6] Lee proposed and implemented an in-process and final inspection procedure with gages. By 1823, the Springfield Armory had introduced gages of the go/no-go design, replacing the judgment of the craftsman with the authority of the gage.

The balance of the 19th century would see continued refinement in the system of inspection with gages. By the turn of the century, inspection was the system of choice to weed out unacceptable variation. During the 1890s, the bicycle industry, a precursor to the automotive industry, provided an excellent study of the early efforts to cope with process variation and quality control. David Hounshell gives the following account of the early efforts of inspection at the Pope Manufacturing Company:

> "Because [Albert] Pope prided himself on the quality of the Columbia [bicycle], he demanded a rigid system of quality control. An inspection department was set up, as in many of the New England armories, with a separate corps of inspectors. Before machining, each drop forging was inspected. About 5% were rejected. After machining, inspectors gaged the critical running parts and examined others for appearance before subassembly. Enameled and nickel-plated parts underwent inspection, and finally the complete cycle was checked. The Pope Company claimed that its cranks were inspected eight times before being sold and some parts as many as a dozen times."[7]

Albert Pope also established a testing department, which carried out destructive testing on its bicycle components. Pope's mechanics devised simple machinery for some of these tests, such as the chain tester, a device that measured the force required to break one. Knowing this average figure, the chain department checked every chain it made on the testing machine by applying a force slightly below the average breaking point.[8]

Increased costs rode in with Pope's system of mass inspection—not just the cost of a 5% rejection rate or the questionable practice of breaking almost half of the chains produced, but also the cost of lost customers and competitive position. Hounshell gives the following account of the effect of mass inspection costs on Pope's competitive position:

"The inspection system and testing department provided benefits but not without costs. When cycle competition began to stiffen, a Pope Columbia/Hartford Cycle dealer complained because the companies would not offer discounts as did other manufacturers. George Pope, president of the Hartford Company, responded to the secretary of his company, the agent 'well knows that we probably put more money into the experimenting departments and into care of inspection, etc., than any other concern in the business.' Despite Pope's insistence on rigorous testing and inspection, his company remained competitive. But it did not maintain its position as the largest producer of bicycles in America."[9]

As the marketplace demanded more mass-produced products with interchangeable parts, industry increasingly found the need to communicate with specification and tolerances. Commerce and trade was now being conducted around the country and in other parts of the world. Specification was used to describe the quality characteristics necessary to satisfy customers' needs in Dallas, London, and New Delhi. Specification and tolerances would be used to define what was to be delivered.

During the early days of armories, specification and tolerances were built into the system of gages and fixtures. When a design changed, new gages and fixtures had to be developed and manufactured, a costly process. While industry was suffering from these added costs during the latter part of the 19th century, innovation was under way in the design and manufacture of precision measuring equipment and work had begun on standards. This innovation paved the way for the use of written specification and tolerances for inspection and acceptance. The manufactured items would now be measured with precision instruments and the measured results compared to the print. This change reduced the cost of manufacturing special-purpose gages and ushered in the era of inspection to print.

Due to the demands for interchangeability, use of standards and dimensioned tolerances were being used throughout industry by the end of the 1800s. The use of specification within a system of inspection was well established within most of the major industries during the late 19th century. No longer would workmen be concerned about the fit, form, or function of a final piece; their job was to make it to print. It would be the job of final inspectors to sort out any products that did not meet specifications. This system of sorting out unwanted variation continues to this day.

The work of Fredrick Taylor would contribute greatly to these efforts at the turn of the century. Taylor and other supporters of scientific management advocated the adoption of a new system for manufacturing. This system had a profound effect on mass production and quality. A major weakness in the Taylor system was the lack of appreciation for variation. Variation was looked upon as something that could be scientifically removed. Once a standard was set, it was the job of the workmen to carry out the plan. This attitude provoked opposition from labor when workers were accused of not performing up to standard and were judged to be below average. The Taylor system allowed management that treated variation in people the same way variation in products was treated: they were either acceptable or unacceptable.

In the 19th century, efforts to eliminate variation from the system were sometimes successful due to the simplicity of the products being manufactured. But as complex systems developed, such as the manufacture of hardware necessary for telecommunications, a new theory and method for understanding variation evolved. Walter A. Shewhart of Bell Telephone Laboratories would contribute the needed theory and methods during the early 20th century.

Shewhart's Theory Behind the Control Chart

How should control limits be constructed? Walter Shewhart stated, "Obviously, the basis for such limits must be, in the last analysis, empirical."[17]

Shewhart used his experience at the Western Electric plant to establish control limits that had proved useful in practice. He emphasized the importance of the economic balance between looking for assignable causes when they do not exist and overlooking assignable causes that do exist. It was also necessary to develop rules that gave an acceptable economic balance for all quality characteristics in a variety of processes.

Shewhart's control chart method provided an operational definition of the concept of common and special causes of variation. The control chart is a statistical tool used to distinguish between variation in a process due to common causes and variation due to special causes.

Control charts help quality practitioners:

- select quality characteristics and statistics to be plotted.
- select a method of measurement and sampling.
- develop a strategy for determining subgroups of measurements (including subgroup size and frequency).
- determine criteria that signal a special cause.

Shewhart called the control limits "three-sigma" control limits and gave a general formula to calculate the limits for any statistic:

Let T be the statistic to be charted. Then,
the center line: CL $= \mu$
the upper control limit: UCL $= \mu + 3\sigma$
the lower control limit: LCL $= \mu - 3\sigma$
where μ is the expected value and the standard deviation of the statistic.

Shewhart emphasized that statistical theory can furnish the expected value and standard deviation of the statistic, but empirical evidence justifies the width of the limits (the use of "three" in the control limit calculation).

The challenge for any particular situation is to develop appropriate estimates of the expected value and standard deviation of the statistic to be plotted. Appropriate statistics have been developed for control charts for a wide variety of applications.

Shewhart presented some statistical theory that can give information on the performance of the control limits. Tchebyshev's inequality can be used to put probability bounds on the limits without making any assumption about the distribution of data or the descriptive statistic. The theorem states that the probability (P) that an observed value of the statistic will lie within the three-sigma limits (as long as the process is stable) satisfies the inequality:

$$P > 1 - \frac{1}{3^2} \quad \text{or} \quad P > 0.89$$

Thus at least 89% of the time, if the process is stable, the plotted statistic is expected to fall within the control limits. Again, this statement requires no assumptions concerning the form or distribution of the data or of the statistic.

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Shewhart's concept of variation

In the 1920s, Shewhart developed a new approach to the study of variation while working on radio helmets at Bell Labs and Western Electric. Shewhart's new concept of variation, which is based on statistical theory, does not replace the previous concepts of variation (in the way the precision gage replaced the go/no-go gage), but is a parallel approach to managing variation.

In 1924, Shewhart attached a graph to a memo written to the director of inspection engineering at Bell Labs. The memo was responding to a request for "the development of an acceptable form of inspection report which might be modified from time to time, in order to give at a glance the greatest amount of accurate information."[10]

Based on this graph (known today as a p chart), Shewhart is credited with developing the control chart. But he went well beyond this original request. Shewhart published the details of the control chart method in the *Bell System Technical Journals* from 1926 to 1930. In 1931, Shewhart published *Economic Control of Quality of Manufactured Product*, which included the theory and application of control charts.

One of Shewhart's most important contributions was determining that variation in a quality characteristic of a process is due to two types of causes:

1. Common causes of variation—those causes that are inherent in the process over time, affect everyone working in the process, and affect all outcomes of the process.

2. Special causes of variation—those causes that are not part of the process all the time or do not affect everyone, but arise because of specific circumstances.

(Note: Shewhart used the term "assignable" instead of "common" and "chance" instead of "special." W. Edwards Deming popularized the common and special cause nomenclature.)

A process that is affected only by common causes is called a stable process. The cause system for a stable process remains essentially constant over time. This does not mean that there is no variation in the outcomes, that the variation is small, or even that the outcomes meet requirements. A stable process implies only that the variation is predictable within statistically established limits.

A process whose outcomes are affected by both common causes and special causes is called an unstable process.

Prediction was the key idea in Shewhart's definition of control: "A phenomenon will be said to be controlled when, through the use of past experience, we can predict, at least within limits, how the phenomenon may be expected to vary in the future."[11]

Through his work at Western Electric, Shewhart found that quality characteristics in manufacturing processes tended not to be in statistical control. He also found that it was possible to identify and remove the causes of the out-of-control situation and bring the process into a state of statistical control.

Shewhart stated three postulates relating to control that formed the rationale for the control chart:

Postulate 1. All chance systems of causes are not alike in the sense that they enable us to predict the future in terms of the past.

Postulate 2. Constant systems of chance causes do exist in nature (but not necessarily in a production process).

Postulate 3. Assignable causes of variation can be found and eliminated.

Based on these postulates, a process can be brought into a state of statistical control by finding assignable causes and eliminating them from the process. The difficulty comes in judging from a set of data whether assignable causes are present. Thus, there is a need for the control chart.[12] (See sidebar, "Shewhart's Theory Behind the Control Chart" on p. 41.)

Comparison of the two approaches to variation

Shewhart's approach to variation (using control charts to understand the causes of the variation) is very different from the approach based on specifications and tolerances. Figure 2 contrasts the two approaches. Shewhart's work did not remove the need for the system of specifications and tolerances, but provided a new way to deal with variation. The lack of understanding of their differences in basis, focus, and goals has caused much confusion among practitioners. Figure 2 highlights some important ideas:

1. The basis for specifications and tolerances is customer needs, while the basis for the control chart is the performance of the process.

2. The control chart studies the variation of a statistic (summary of the base data), while specifications usually apply to the base data. (Note: an individual control chart does study the variation in the base data.)

3. Because of 1 and 2, there is no direct relationship between the status of a control chart and the acceptability of process outcomes. A process can be out of statistical control (affected by special causes), but all of its outcomes within specifications. Conversely, a process can be in statistical control while producing outcomes outside specifications.

4. When studying variation, or comparing methods of controlling variation, it is important to be clear about the aim of the method. The goal of control charts is very different from the goal of systems based on specifications and tolerances.

The concept of process capability allows information from a control chart to be used to determine the acceptability of process outcomes.[13] A capability analysis brings together the voice of the process (the control chart) and the needs or requirements of the customer (specifications and tolerances).

Applications of Shewhart's theory and methods

Since 1931, control charts have been introduced in manufacturing, assembly, and other types of production processes throughout the world. Control charts are called Shewhart charts in some parts of the world to distinguish charts based on Shewhart's theory from other types of charts.

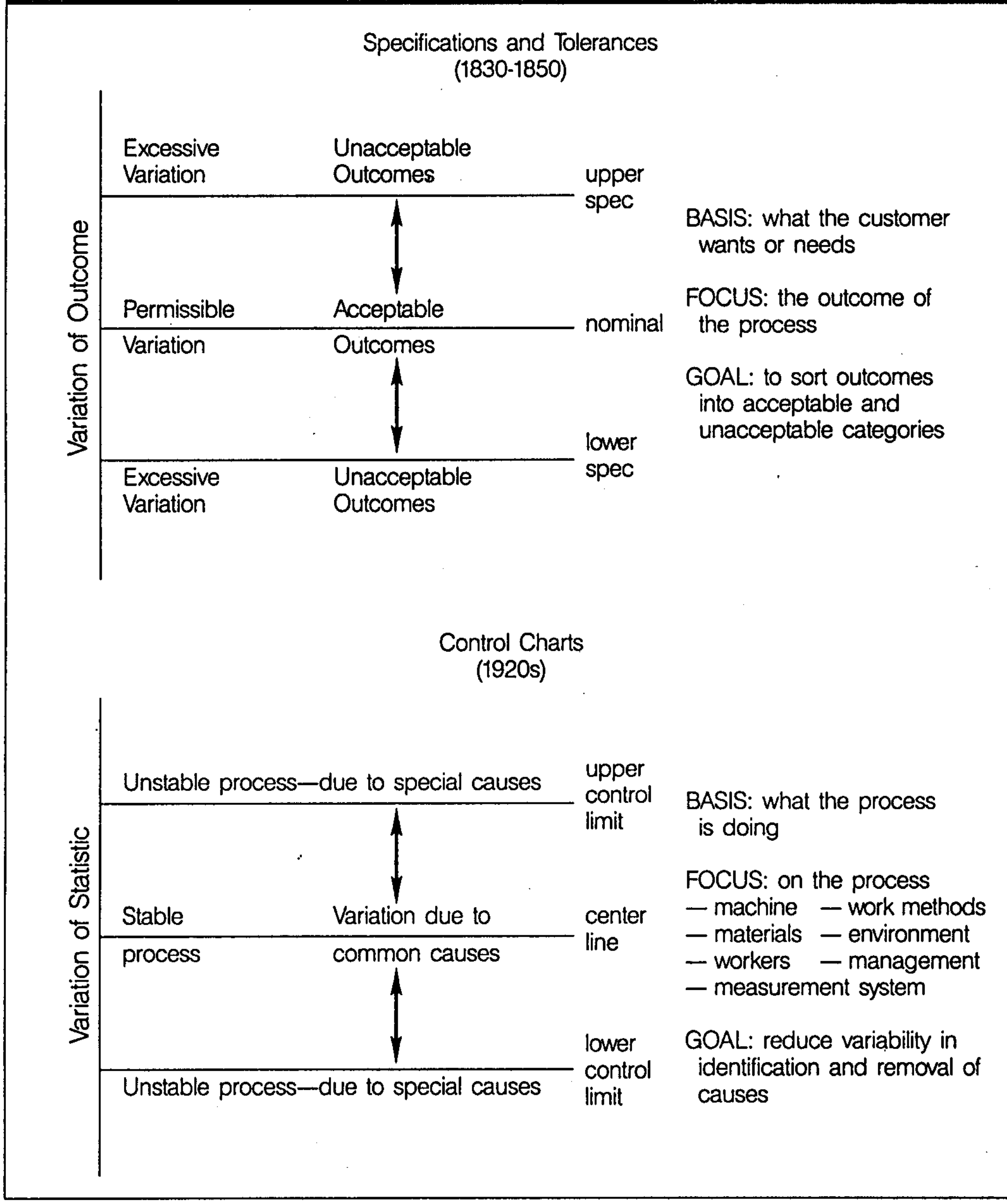
During World War II, 10-day courses that taught Shewhart's control chart method were offered to U.S. companies that supplied the war effort. The application of control charts proliferated after these classes, but the applications were focused on quality control, solving problems, and inspection. Because of management's lack of understanding of the control chart theory or method, these efforts diminished after the war.

When Deming worked with Japanese managers and engineers in the early 1950s, part of his teaching included Shewhart's theory and the control chart method. The Shewhart control chart became a basic tool for Japanese manufacturing and production operations.

A number of people have developed modifications and extensions and have attempted improvements to Shewhart's control charts. The literature since 1945 has presented many of these proposals. Much work has been done attempting to improve the "economics" of the control chart method by offering different control limits and optimum sampling strategies.[14]

Others have tried to apply Shewhart's concepts to situations that focus on inspection, where the aim is to identify "good" and "bad" outcomes of a process (applying the control chart to the left side of Figure 2). Three examples are modified control limits (1945), precontrol (1954), and acceptance control charts (1957). Often, these proposals and comparisons lose track of the basic aim of the Shewhart control chart method: to distinguish between variation in a process due to common causes and variation due to special causes. For example, in a recent publication on quality addressed to management, a control chart for a stable process was described as "indicating that all is well and that production should continue full speed ahead, when, in actuality, the process is likely to produce a totally unacceptable rate of defective parts!" This lack of understanding by quality practitioners of the principles behind the Shewhart control chart continues to be a major barrier to the application of the control chart method. Deming is one of only a few professionals who have consistently tried to keep Shewhart's original concepts alive in the face of this confusion.

Figure 2. Comparison of the Two Approaches to Managing Variation



Deming emphasizes that Shewhart's concepts of variation are just as applicable to service and administrative processes (and the management of processes) as they are to manufacturing. The control chart method can be used throughout organizations.[15] Top managers can use control charts to study variation in sales; supervisors can use them to assign responsibility for improvement of a process; administrative personnel can use them to identify opportunities for improvement; and operators can use control charts to know when to adjust a process.

The rationale for the continued use of Shewhart's control limits can be summarized as follows:

1. The limits have a basis in statistical theory.

2. The limits have proven, in practice, to distinguish between special and common causes of variation.

3. In most cases, use of the limits will reduce the total cost due to overreaction and underreaction to variation in the process.

4. The limits protect the morale of workers in the process by defining the magnitude of the variation that has been built into the process.

Variation in the 21st century

Just as the dawn of the 20th century introduced complexity in manufacturing and created the need to understand variation from common and special causes, the 21st century will place even greater demands on society for statistical thinking throughout industry, government, and education. The continued increase in complexity of products will make variation that is insignificant today a critical issue tomorrow.

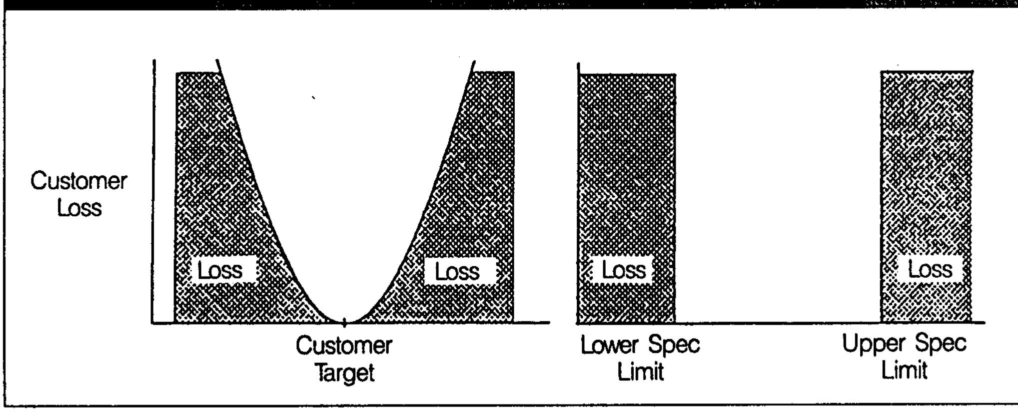
Shewhart's methods have been around since 1924 and have been published since 1931. Yet they are not well-known outside the quality community and are not generally practiced. Where they are known, there is resistance. Many engineers today believe that variation is not an issue and can be designed out of process. More than 50 years ago, professor H.A. Freeman explained the resistance he encountered at the Massachusetts Institute of Technology in promoting the new methods of statistical quality control:

" . . . a deep-seated conviction of American production engineers that their principal function is to so improve technical methods that no important quality variations remain, and that in any case, the laws of chance have no proper place among 'scientific' production methods."[16]

In other words, these engineers believed in the myth of exactness and relied on the technology of their day to eliminate variation. Variation was simply ignored, and the need to understand statistical methods was not apparent.

Companies' reliance on machines and gadgets to eliminate variation continues to this day and may follow us into the 21st century. Genichi Taguchi recently popularized the concept of the loss function to focus the impact of variation on quality. He has presented the idea that variation from a desired target contributes to a loss to society. Figure 3 contrasts this view with specification and tolerances.

Figure 3. Specification vs. Loss Function



Taguchi argues that the idea that loss somehow jumps in value at the specification limit does not seem to reflect the real world. Taguchi's quadratic loss function takes the form of a parabola and shows that the loss is continuous from some desired target. There are many examples of the loss in industry when specifications were met and the product defective (i.e., tolerance stack-up). The loss function as a view of managing variation will continue to be a useful model well into the next century.

The 21st century will place more emphasis on people than ever before. The demands for information and knowledge will become more pronounced. Helping people learn will replace the current emphasis and importance placed on machines and technology. Technology can be purchased in the global marketplace; it is the knowledge within individuals in a company that will determine the success of one company versus another. The organizations that nurture learning will be the leaders in the next century.

This learning organization will find it necessary to deal with variation in people—how they learn, their skills, and their physical capabilities. Change in the next century will demand more leaders than managers. Leaders will have to have knowledge of variation, theory of knowledge, psychology, group dynamics, and of systems theory. Deming refers to this as profound knowledge. Profound knowledge would transform most managers into leaders today and society would benefit greatly. Most managers get by without this sort of knowledge today. In the future, these ideas will be viewed as minimum expectations for leadership. The learning organization will be built on a foundation of profound knowledge for the 1990s and common sense for the 21st century.

Acknowledgments

We would like to thank the other members of Associates in Process Improvement and the *Quality Progress* reviewers who made suggestions to improve this paper. In addition, Oz Godsey was kind enough to loan us his 1940 to 1950 back issues of *Industrial Quality Control*.

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