

Variability and Capability: The Foundation of Competitive Operations Performance

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From an operations perspective, there are six primary competitive priorities on which a company can elect to focus: cost, quality, service, flexibility, time, and technology. Two tactics improve the performance of these priorities: enhancing current process capability by reducing variability, and using technical innovation to define new “breakthrough” capabilities. This paper discusses the importance of both tactics and reviews specific case studies that demonstrate their significance.

Introduction

During the early 1980s, leading educators¹ of manufacturing strategy maintained that there were four competitive priorities in operations: quality, service, flexibility, and cost. Recently, because of a change in the competitive paradigm, the priority of time has been added,² as it relates to the introduction of new products and the reduction of the interval between receiving and filling an order. We maintain that there is a sixth priority, manufacturing technology. After all, it would be pointless for a company to have the lowest cost structure and the highest quality values if it did not possess the basic technology to manufacture a product.

We believe that there are two strategies for enhancing the performance of the six competitive priorities: introducing technical innovation and reducing process variability by improving process capability. We also believe that any successful manufacturing company must have a balanced program that embodies both approaches. To focus solely on reducing variability could place a company in jeopardy, because it would render the company vulnerable to a competitor with a “breakthrough” technology. At the other extreme, to concentrate only on technical innovation without continuously improving the existing technology and processes could also be lethal. Ambitious technical innovations require patience and are not always successful. Even if an innovative product or process is developed, it does not ensure dominance when competitors enter the market.

Over the years, AT&T manufacturing

has led a balanced attack on improving manufacturing performance. In its July/August 1990 issue, the *AT&T Technical Journal* discussed one example of how AT&T's manufacturing efforts had improved its process capability. This issue will add to that discussion, but it will emphasize how technical innovation affects manufacturing.

Process Capability in Competitiveness

Since Shewhart's³ introduction of control charts in the late 1920s, the heart of process control has been consistency of production. Classical control charts were designed to highlight inconsistent (“out-of-control”) observations within a process. Operators and engineers fine-tuned a process by combining control charts with traditional quality improvement tools, such as Pareto analysis and fishbone diagrams. Pareto charts use a graphical display of problem source versus frequency of occurrence to expose the largest sources of problems. The fishbone diagram (also called the cause-and-effect diagram) starts with an effect (usually a problem or failure) and works backward to identify all possible causes of this effect. Over a period of time, fine-tuning techniques such as these would decrease variability and improve process capability. A convincing argument can be made that this gradual, unending improvement (what the Japanese call *Kaizen*⁴) should be the major competitive priority in manufacturing today. (The concept of *Kaizen*, developed by Masaaki Imai, encourages continuous improvement to a process or organization by involving everyone in implementing

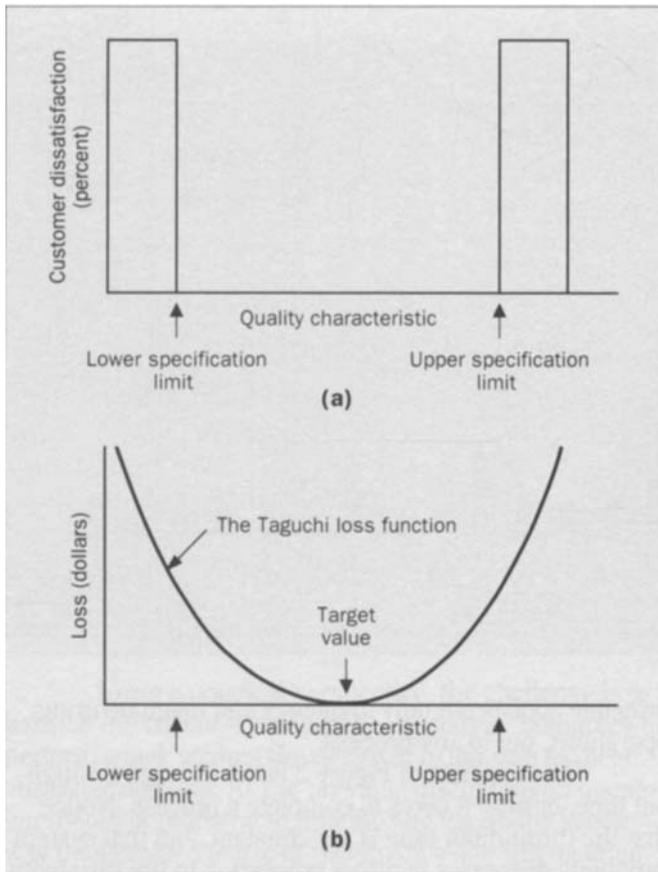


Figure 1. Two views of how variability affects customer satisfaction. (a) The digital view (as discussed in Bhote), in which the customer is 100-percent satisfied no matter how narrowly a parameter falls inside the product specification. If a parameter falls outside, the customer will be 100-percent dissatisfied. (b) The Taguchi view, in which customer satisfaction is represented as a curve. At zero, the customer is satisfied. As the parameter moves up the curve, customer satisfaction decreases.

incremental changes in every aspect of work.)

Initially, the basic premise of reducing variability to improve quality was applied both to manufacturing output and processes. To ensure customer satisfaction, these concepts have been updated and extended to other areas of operations.

Customer Satisfaction. Bhote⁵ states that variability is evil and excess variability is the graveyard of poor management. Variation creates customer dissatisfaction and, eventually, economic loss. Consider Figure 1a (from

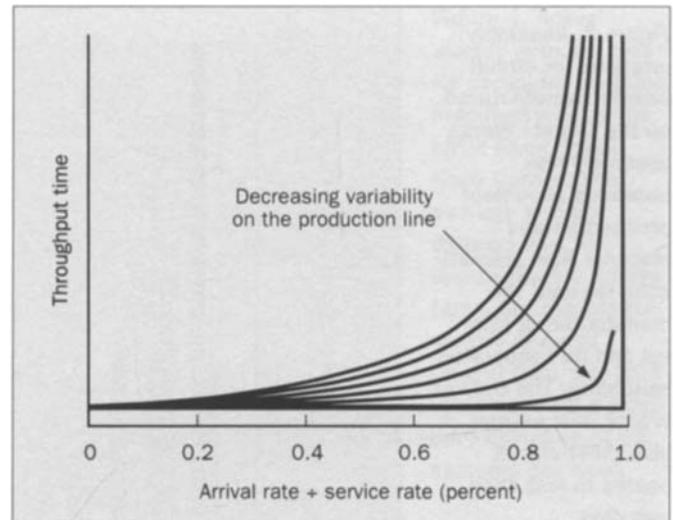
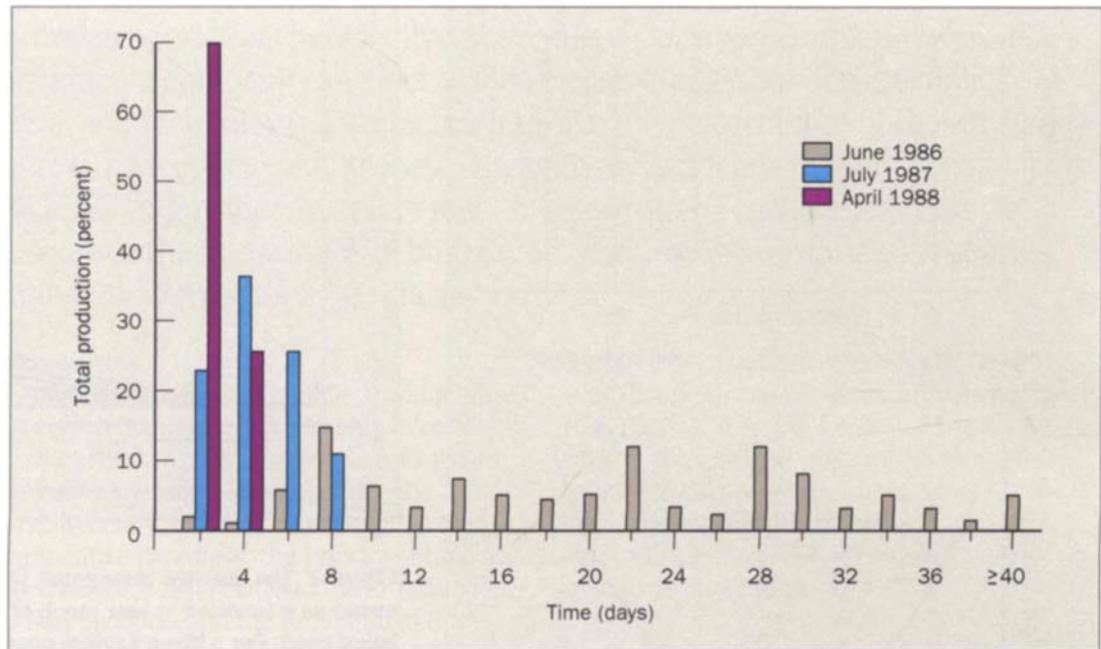


Figure 2. The average throughput time of a single-server queue as a function of how much of the system's capacity is being used. For a given system capacity, the throughput time depends on the degree of variability in the system.

Bhote), which portrays the traditional view of product specifications. No matter how narrowly a parameter falls within a specification limit, the customer will be 100 percent satisfied; no matter how narrowly a parameter falls outside a specification limit, the customer will be 100 percent dissatisfied. In reality, customer satisfaction cannot be measured in digital form, but rather is reflected by the curve shown in Figure 1b, which represents the view of Taguchi.⁶ According to Taguchi, customer dissatisfaction is at zero when a product parameter is at, or very close to, the target value. It increases as the parameter moves away from the target value toward one end or the other of the specification limit. Taguchi maintains that loss of customer satisfaction can be measured in monetary terms.

A case study that clearly shows the effect of variability on customer satisfaction was described by Donald Peterson, the former chairman of the Ford Motor Company.⁷ Although both the Mazda Hiroshima, Japan, and Ford Batavia, Ohio, plants manufactured transmissions from the same design, the final products were dramatically different. The Japanese transmission was well liked by customers, while the one made in Ohio was not. Customers complained that gears on the Ford transmissions shifted poorly. When Ford engineers took the two transmissions apart, they could actually see a difference. The

Figure 3. Assembly intervals for circuit boards manufactured on the Denver Works assembly line. Improved shop-floor procedures and material flow dramatically lowered the manufacturing interval and its associated variability. The Denver Works now assembles most circuit boards in less than two days.



parts used in the Mazda transmission were exceptionally well manufactured and finished, and every measurement fell within extremely close tolerances. Even though the Ford transmissions met the specifications, much more variability existed in parts dimensions from one transmission to another. This variability in parts dimensions, although within specification, led to increased variability in the final product. When the final product was assembled, the Ford transmissions varied in performance and had a lower level of customer satisfaction.

Time. The review of elementary queueing theory described in References 8 and 9 discusses the relationship between variability and time. Figure 2 shows the average throughput time of a single-server queue (such as that associated with a single machine on the factory floor) as a function of how much system capacity is being used. This is measured as the ratio of the arrival rate of entities to the rate at which the resource (or machine) can operate. For a given percentage of system capacity, the throughput time depends on the degree of variability in the system. In fact, if variability were removed, the throughput time would equal the service time, the time required to perform the designated task. This would continue until the arrival rate exceeded the service rate (the rate at which a customer need is satisfied). At this point, a queue would form and grow without bounds. This basic

principle applies not only to queues and manufacturing operations, but to any process.

The ordinate of Figure 2 is the average throughput time, or time it takes to complete a process. Notice that the throughput time is not constant, and that system variability decreases in direct proportion to the variability in throughput time. Consequently, to assess the performance of a process, we must measure both the throughput time and its variability.

There are two sources of variability: the arrival rate of entities and the service rate. On the manufacturing floor, the arrival rate at a given workstation may fluctuate for many reasons, such as unpredictable arrival rate of customer orders, unsynchronized arrival rate of work or quality deficiencies from preceding operations, or equipment failures. Similarly, the service rate may be affected by equipment problems, variable setup times, lack of clear instructions to the machine operators, quality problems at the workstation, a lack of operator skills, etc. Even if equipment is being used at an economically desirable capacity, such as 80 percent (see Figure 2), small decreases in the service rate (which use a higher level of the system's capacity) lead to a large increase in throughput time, or manufacturing intervals. Furthermore, increasing the variability of either the arrival rate or the service rate also leads to a large increase in throughput time.

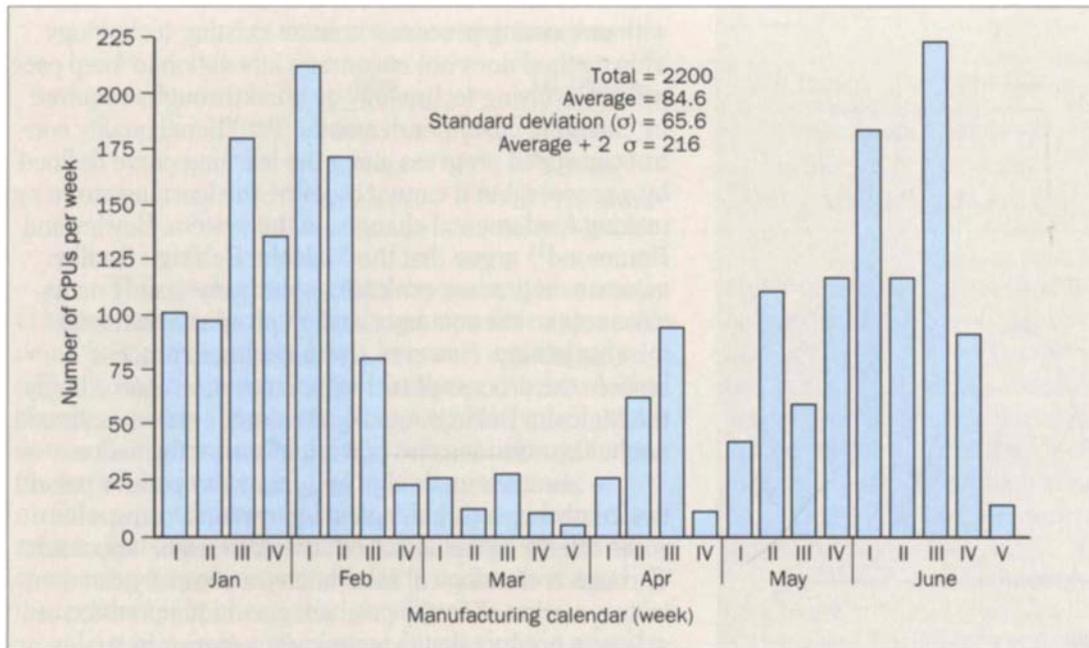


Figure 4. Actual weekly demand data for computer systems manufactured at the Little Rock Operations Center. The average weekly demand was for approximately 85 systems, but the actual weekly demand ranged from 5 to 225 systems, with a standard deviation of 65 systems per week.

From a practical perspective, the challenge is to balance the cost of providing the capacity or resources to perform a task against the desire of being able to meet customer demand. As the previous discussion on queuing theory demonstrated, minimizing variability is one way to optimize the use of resources while still meeting customer demands.

Figure 3¹⁰ illustrates a success story at the AT&T Denver (Colorado) Works. Manufacturing intervals for a certain capacity were slashed by systematically reducing internal process variability using process improvement techniques. The net result is that the Denver Works is now able to manufacture more products in shorter intervals using fewer resources.

Better management of the external forces that create variability also reduces manufacturing intervals. For example, the AT&T Little Rock (Arkansas) Operations Center manufactures customized, built-to-order computer systems for a major customer. Contractually, AT&T is required to deliver these systems within a fixed interval or risk incurring penalties. Their challenge is to meet this goal in the face of highly volatile demand, customized orders with configurations defined at the last moment, and customers who demand at least 95-percent shipping performance.

Figure 4 shows the data for actual weekly

demand over a six-month period. The average weekly demand was for about 85 systems, but the *actual* weekly demand ranged from 5 to 225 systems. The standard deviation for this nonnormal distribution was about 65 systems per week. To exceed 95-percent shipping performance, the Little Rock Operations Center needed to maintain a production capacity of greater than 220 systems per week and hold considerable amounts of inventory, both of which were costly. Every attempt was made to streamline the internal processes and to operate at capacity levels low enough to minimize cost and still meet customer commitments. Unfortunately, operating at the edge of capacity levels during peak demand periods places the Little Rock operation on the steep part of Figure 2, where a large increase in demand variability would result in a large increase in the throughput time, or manufacturing interval. Although generally pleased with the service level (except during peak periods) and the quality of the outgoing product, the customer was not happy with the cost of the service, which included maintaining underutilized capacity and resources during nonpeak periods. Recognizing demand variability as one of the root causes, the Little Rock Operations Center minimized it by:

- Requesting longer delivery intervals (greater than 30 days) for some customer orders. The factory could

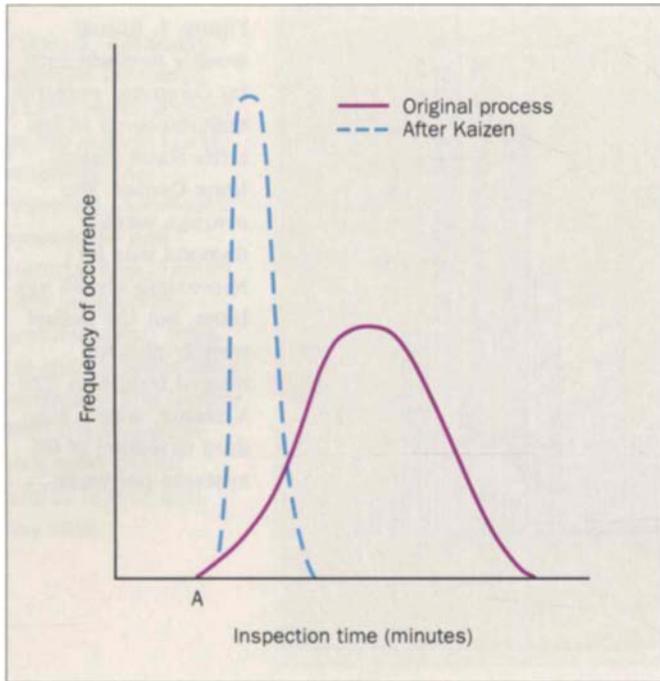


Figure 5. A typical distribution of some quality parameter over a given period of time before and after Kaizen was applied to the process. Surface-mount circuit-board assemblies were visually inspected. The lower bound (point A) remained fixed in value because of physical limits. As the mean inspection time approached point A, it became increasingly difficult to improve the process.

then adjust order schedules to equalize production levels and minimize variability.

- Working with the customer to minimize the peak period by leveling the demand. This reduced demand volatility and allowed manufacturing to cut the production capacity (which, in turn, cut the cost) but still maintain high shipping performance.
- Adding other products to the production line. These help to buffer peaks and valleys in the production schedule and spread the cost of operating the production line.
- Asking the sales force to encourage customers to order standard configurations, which take less time to make and which minimize inventory.

Technological Innovation and Competitiveness

Unfortunately, reduction of variability only addresses the narrow set of quality issues associated

with an existing process within an existing technology. This method does not encourage innovation to keep pace with an evolving technology or breakthroughs required by changing customer demands. Traditional quality control can speed progress along the learning curve defined by a process, but it cannot redefine the learning curve by making fundamental changes in the system. Bowles and Hammond¹¹ argue that the Malcolm Baldrige Quality assessment process evaluates a company mainly on its closeness to the customer and on programs that minimize variability. However, the assessment process ignores the process of technical innovation. Accordingly, the Malcolm Baldrige quality assessment process should not be the sole measure of world-class performance.

Another method of assigning competitive priorities emphasizes technological innovations, using what some call the “giant leap,” or “breakthrough,” approach. Through technological innovations, a company can dominate a market share by producing a unique product, or at least a product that is technically superior in quality or performance. If a company uses only variability reduction to lower defect levels and fails to introduce innovations in a manufacturing process, the process will encounter “sticking points,” or quality thresholds. When these thresholds are reached, procedures that had previously maintained the current quality level can no longer improve the process significantly. At this point, only a fundamental change to the system (either in technology or methodology) will keep it from remaining stalled. This fundamental change redefines the factory’s learning curve, establishing a new learning curve and propelling the factory toward a new, improved quality, or performance, threshold.

Figure 5 illustrates typical distribution of a quality parameter over a given period of time. For this discussion, assume that Figure 5 presents data drawn from a surface-mount circuit-board assembly shop. The quality metric is the time it takes to visually inspect a printed wiring board after the soldering process. Over time, applying Kaizen reduces the variability of the process, as Figure 5 shows. The reduction in variability is not symmetric; the variability is decreased by eliminating the long inspection times. The lower bound (designated by A) remains fixed in value by physical limits. No matter how much the inspection operator tries, it is impossible to manipulate the microscope more quickly than A. As a result, Kaizen tends to decrease variability asymmetrically, leading to a decrease in mean inspection time.

Table I. Typical 1-Mbit DRAM Data

Item	1st Design	2nd Design	3rd Design
Design rule	1.2 μm	1.0 μm	0.9 μm
Die size	65.5 mm^2	51.8 mm^2	44.2 mm^2
Access time	100/120/150 ns	80/100/120 ns	70/80/100 ns

This method precipitates only a limited amount of improvement. As the mean inspection time approaches point A, improving the process becomes increasingly difficult, and the mean asymptotically approaches A, the process "quality threshold." No matter how much additional effort is made, the process will not improve unless the paradigm is changed. For this example, using a machine vision system (i.e., a machine-based inspection system that can automatically assess solder quality by comparing it to preset standards) to replace a manual inspection might change the paradigm.

Manufacturing Technology. Innovations in manufacturing technology work in harmony with techniques to reduce variability in the manufacture of memory devices. To illustrate how breaking through quality thresholds relates to variability reduction, consider the highly competitive environment of an integrated circuit memory device. The dynamic random access memory (DRAM) device is a high-volume product manufactured by many vendors and sold with a narrow margin of profit. The memory device is categorized by the amount of memory available to the user (measured in bits) and how quickly the memory can be accessed (measured in nanoseconds [ns]). Under the naive assumption that memory device prices are entirely market-driven, the three major factors that determine price are available memory, gross yield, and device speed.

Available memory and device speed are determined by their manufacturing technology. The manufacturing technology is defined by design rules, which determine the minimum distance between design features on the device. As design rules shrink, the density of the features increases, as evidenced either in the available memory of the device or the number of devices made per wafer. The 64-kilobit (kbit) DRAM was initially designed for high-volume production using 3.5-micrometer (μm) design rules. (For those unfamiliar with this measure, consider that a human hair is about 50 μm thick.) Further changes to the process shrank the design rule to 2.5 μm , which allowed the producer to

either make the present 64-kbit DRAM smaller and faster or to expand it to a new 256-kbit DRAM device. In each new device generation (industry estimates a new generation every three years), available memory increases and access time decreases. Introducing a generation of new devices requires more than techniques to reduce variability; it often calls for innovations in machinery and processes to increase the accuracy required for smaller design rules.

Within each technology, the two driving price factors are *yield* and *speed*. Yield can be increased in one of two ways. Variability reduction encourages the slow, unending process of identifying and eliminating problems, each of which appears to be minor when viewed in isolation. This is particularly effective in a mature process. Overall yield is increased (as illustrated in Figure 5) through a large number of small improvements, each marginally improving the yield. Product redesign and process changes also improve yield and speed within a given technology, which, in turn, can lead to larger yield increases over short periods of time.

Table I shows typical changes. As a rule of thumb, within each technology in the memory device industry, a new design is issued every 12 to 18 months. By reducing the size of the device during a redesign, more devices can be made using the same raw material, which would instantly increase the number of devices produced. (The die size in the first design listed in Table I is 50 percent larger than the die size in the third design.) Reducing the device size also increases the speed of the device; the average access time for the three designs decreases from 120 ns to 100 ns to 80 ns.

Of the three possible access times for each design shown in Table I, the average access time is assumed to be the middle value. The three values for each design reflect the variability of the process. As a process matures and the variability is reduced, prices reflect the decrease in the variability of access times. In March 1988, a 100-ns 256-kbit DRAM cost 56 percent more than its 150-ns counterpart. Three months later,

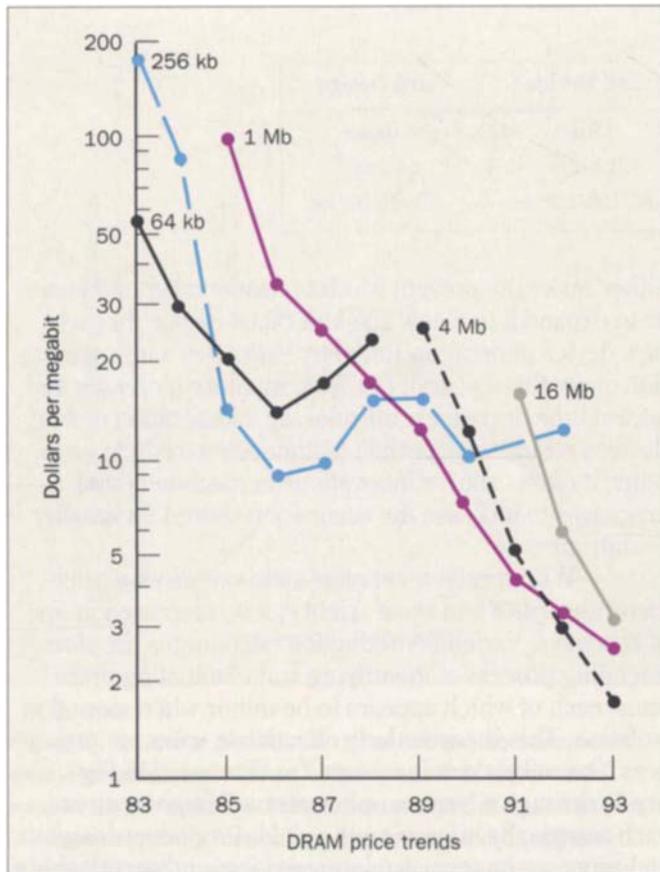


Figure 6. The summary of DRAM price trends shows that every three years, on average, the price efficiency of the new technology overtakes that of the old technology.

the same DRAM cost only 8 percent more. As variability is driven down, larger quantities of faster devices are made for a smaller premium.

Figure 6 shows a summary of price trends in the DRAM business. On average, every three years the price efficiency of the new technology overtakes that of the old technology. (Until 1985, the 64-kbit DRAM was the most cost-efficient DRAM. Today, the 4-megabit [Mbit] DRAM is projected to be the most cost-efficient.)

Vendors who compete successfully in this field must pursue both manufacturing efficiency through reduction of variability and more powerful products through technological innovation. The most efficient 64-kbit DRAM producer in the world would go out of business if it did not manufacture other products. Con-

versely, the most technologically advanced manufacturer would also close its doors if it failed to reduce process variability. There is a premium associated with entering the market first with memory devices, but the huge demand quickly negates any early entry advantage. If reduction of variability is sacrificed to technological innovation (a fault traditionally attributed to Western industry), a company cannot survive. However, a company pursuing reduction of variability to the exclusion of innovation (in a changing market) is doomed to failure as well.

In This Issue

This issue focuses on technical innovation that supports both quality and productivity improvements in manufacturing.

Parker and Harrison discuss environmental stress testing (EST). In the past, burning-in, or "soaking," a product at elevated temperatures during the manufacturing process was used to reduce failures in the field. However, burn-in was not always effective and had limitations. Since 1990, environmental stress screening, or testing, has become widespread in the industry. During EST, the product undergoes rapid thermal cycling to identify latent defects. Parker and Harrison review EST and describe innovations they have made in introducing product testing during the thermal cycling process.

As the physical features of electronic products become finer, it is increasingly difficult, if not impossible, for humans to ascertain the quality of an assembly process accurately (e.g., solder joint quality). To date, the state-of-the-art process control system has been a machine vision system that captures a two-dimensional image. Amir et al. describe a three-dimensional vision system that measures solder paste volume and inspects circuit-board assembly quality.

Electronic components are usually assembled by hand on a circuit board. For high-volume circuit-board codes (where a code denotes a unique circuit-board design), progressive hand assembly works best, while high-mix, low-volume codes are usually relegated to the hopelessly antiquated batch assembly process. W. A. Elliott breaks from the classical mode and describes how to apply progressive assembly techniques to low-volume codes.

With time-to-market becoming an increasingly important competitive priority, programmable integrated circuits that provide customized functionality play an

expanding role. Unfortunately, large numbers of continually changing programmable logic devices create a logistical manufacturing nightmare. C. G. Bess, W. W. Jones, and E. E. Lewis designed and developed a highly flexible programmable logic device programming and placement machine.

Although cable manufacture is not a glamorous aspect of electronics manufacturing, it is critical to the manufacturing process. C. R. Anderson, A. R. Brown, and G. G. Semens describe how they automated the production of cables to improve quality and reduce cost.

Small increases in service rate can lead to large decreases in throughput time. B. L. Farrell et al. discuss a new approach to monitoring service effectiveness in an integrated circuit manufacturing environment, with examples that show its effect on service time.

Finally, B. D. Tull, Jr., describes the introduction of a modern, three-dimensional, solids modeling computer-aided design/computer-aided manufacturing (CAD/CAM) system that slashes the time and cost it takes to manufacture plastic parts.

Summary

From an operations perspective, cost, quality, service, flexibility, time, and technology are the key competitive priorities. For a manufacturing concern to improve these metrics, it must continually strive to improve its operational process capabilities and to introduce technological innovation. To achieve one without the other will yield, at best, short-term gains without sustaining world-class performance.

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