Quality Control and Management of Variation—Assessing Cost Benefits

Zafar U. Khan, Alahassane Diallo, and Curtis F. Vail

EXECUTIVE SUMMARY

- Improved quality can create competitive advantage through lower costs and products that stand out from those of competitors.
- The ground-breaking work of quality gurus such as W. Edwards Deming, Walter Shewhart, and Genichi Taguchi emphasizes reducing variation as the way to achieve quality manufacturing.
- Reduced variation (according to both Deming and Taguchi) is the key to both quality improvement and cost reduction.
- This article discusses an automotive body assembly plant where prevention—identification and elimination of the root causes of variation problems—led to both lower variation and higher quality.
- Average costs at the plant declined when variation declined, and the plant's yield increased significantly as variation decreased.
- Cross-functional teams, which were empowered with a combination of managerial support and technology, helped the plant achieve low variation and thus became a low-cost, high-quality producer.

Most discussions about manufacturing quality emphasize controlling variation, a concept developed by pioneering thinkers such as W. Edwards Deming, Walter Shewhart, and Genichi Taguchi. Managing variation is particularly applicable to settings such as an automotive body assembly where hundreds of interchangeable parts are assembled (Sudhakar, 1995; Kim and Liao, 1994; Anderson, 1990).

Taguchi's methods for *off-line* quality control (e.g., experiments for product and process design) have found overwhelming accep-

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tance and have been reported to be quite successful. Major U.S. companies that have adopted Taguchi's methods (Noori, 1989) include:

- Chrysler Corporation
- Ford Motor Company
- General Motors
- ITT
- Xerox
- Lucent Technologies (formerly Bell Laboratories)
- United Technologies
- 3M Company

Taguchi's ideas about *on-line* quality control (e.g., reducing process variation for overall quality improvement and "centering" process means on design specifications or "design intent") are also widely discussed and accepted, but until now few practical applications have been reported.

This article quantifies the benefits of reducing variation at an auto body assembly plant of a major automobile manufacturer—a plant that *Business Week* ranked as one of the top 25 plants in the United States. This article refers to the plant as "RV Company" (a pseudonym), and the data—including cost savings from scrap reduction, labor, and other manufacturing expenses (OME)—have been indexed to disguise the actual amounts yet permit valid comparisons.

RV Company's experience clearly shows that as variation fell, quality increased (Ceglarek, Shi, and Wu, 1994; Cao and Zhou, 1993) and costs declined. This study provides objective evidence to disprove the still widely held belief that higher quality necessarily means higher costs.

REDUCING VARIATION

The work of Deming, Shewhart, and Taguchi emphasizes management of variation. For a summary of their work (including explanations of the vocabulary used), see the sidebar in this article entitled "The Cost of Quality: Historical Development of the Concept." Shewhart developed a widely used control chart method that identifies whether variation in a process is attributable to *common* or to *special* causes.

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Both Deming and Taguchi believed that variation causes quality costs to be incurred and that external failure costs are the most significant. Unfortunately, *external* failure costs are hidden and not measurable, though management cannot afford to ignore them. To control quality costs, Deming believed, companies should reduce process variation. Deming held that quality improves as variation decreases.

Hidden Quality Costs

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Both Deming and Taguchi argue that there are hidden quality costs even for parts or products whose important characteristics fall within tolerances. Their ideas have special significance for manufacturing operations such as RV Company's auto body assembly, in which more than 300 distinct parts are put together on the moving assembly line. When so many parts are assembled, even if each individual part is "good" (i.e., each part's dimensions are within specifications), an imperfect product or inefficient process may result because of the "tolerance stack-up problem."

A focus on variation reduction provides a methodology and process for improving the quality of auto bodies.

A focus on variation reduction provides a methodology and process for improving the quality of auto bodies. Taguchi's quality loss function implies that quality decreases and cost increases as critical dimensions vary from the design intent. Thus, the key to both quality improvement and lower overall costs is reducing variation in *all* stages of the body assembly process, from parts to subassemblies to the final product.

Cross-Functional Problem Solving

Permanent reductions in variation cannot be realized without an understanding of the *root causes* of variation. This requires a systematic, data-driven, and knowledge-based effort to identify and eliminate variation (Ceglarek, Shi, and Wu, 1994; Cao and Zhou, 1993). In an auto body, variation may be attributed to either *component variation* or variation introduced *during assembly* (Wearring and Cola, 1991).

Most variation problems are caused by one of the following:

- Problems in product or process design;
- Installation problems;
- Maintenance problems; or
- Poor components from suppliers.

Given the range of these problems, solving them requires a team effort. Product and process design engineers, production and operational employees, and suppliers, among others, must be involved, and top management must be committed to an organizational philosophy of *continuous improvement*.

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Systematic Problem Solving

The cross-functional teams (which were led by floor-area managers) at RV Company demonstrate the effectiveness of systematic problem solving to reduce variation. As Exhibit 1 demonstrates, these cross-functional teams achieved the following goals and objectives (Ceglarek, Shi, and Wu, 1994; Zhou and Cao, 1994; Cao and Zhou, 1993):

- A 2mm variation for *body-in-white* assemblies (that is, a partially completed auto body consisting of underbody, roof, and side panels before painting and installation of the powertrain) and a 1.5mm variation for subassemblies within an 18-month period.
- *Body-build* (all the body-in-whites assembled to date) continuous improvement of quality in record time through the use

The Cost of Quality: Historical Development of the Concept

Quality for manufacturing operations has been defined as conformance to design specifications. Design specifications generally consist of a nominal, or target, value plus a tolerance (to accommodate process variation) of some critical parameter or characteristic. From the perspective of total quality management, however, conformance to specifications that do not have their origins in customer satisfaction may not "delight" customers.

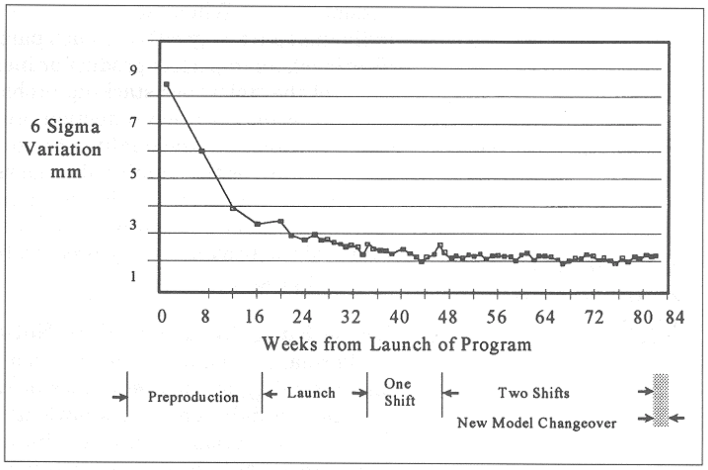
Traditional Quality Concepts

In the traditional view of quality, products, subassemblies, or parts are judged to be either *acceptable* or *unacceptable* (defective). These defective items are either reworked to conform to the specifications or scrapped. Under this traditional view of quality, all acceptable parts or products are considered to be of the same quality.

From a cost-of-quality perspective, most companies' cost systems track only costs incurred in the production of defective parts or products—that is, production and rework costs (direct material, direct labor, and manufacturing overhead) for units that do not meet quality control standards (the specifications).

These costs are further categorized as *normal* and *abnormal*. Many accounting systems report only "abnormal" loss, which is used as feedback for control and corrective actions. The premise for reporting only abnormal loss is that the causes of abnormal loss are controllable in the short run, but that normal loss is inherent to any production process and cannot be controlled without costly changes in process or product design.

Exhibit 1. Body Variation Continuous Improvement



of automatic, laser-based, 100 percent in-line measurement systems. (Variation reduced from 8.5 mm to below 2 mm.)

- A systematic analysis of variation problems made possible by having an in-line, laser-based gauging system that provided sufficient and timely data for the analysis.
- Integration of the cross-functional team's knowledge base concerning design and manufacturing processes with the analysis of variation, which made it possible to identify the root causes of variation quickly.

Exhibit 1 uses the term *Six Sigma*, which was popularized by Motorola and adopted by RV Company, among others, as a quality program that sets a goal of 3.4 defects per 1,000,000 in any process. Sigma refers to standard deviation, and six sigma means that 99.9997 percent of key-dimension measurements fall within acceptable limits.

Role of In-Line Measurement Systems

RV Company achieved continuous improvement of quality in the body-build area by reducing variation, which meant that products came closer to the original design intent. To implement continuous process improvement, which consists of identifying and eliminating the root causes of variation problems, variation must be detected in a timely manner. Specifically, world-class variation requires 100 percent in-line measurement in real time to track performance.

In-line measurement systems collect data continuously, so they give information quickly and help meet world-class targets for variation of auto bodies much faster. To maintain and improve the level

Contemporary Quality Cost Concepts

A second stage in the development of quality cost systems draws on the work of Joseph M. Juran, William Maser, Philip B. Crosby, and Armand V. Feigenbaum, who developed the basics of quality cost measurements. They classified quality costs into the following categories (Albright and Roth 1992):

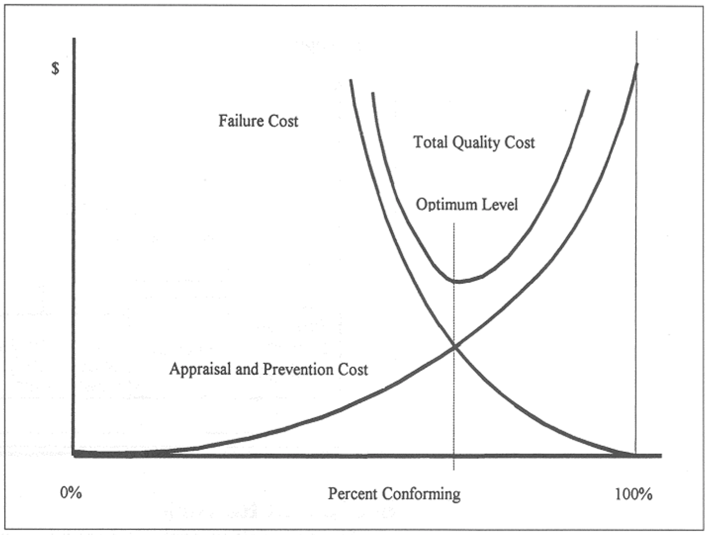
- Prevention costs.
- Appraisal costs.
- Failure costs.

Prevention and appraisal costs are called *cost of conformance*; failure costs are called *cost of nonconformance* to quality control standards.

The advantage of these cost-of-quality classifications is that they provide a framework for quantifying and minimizing the total cost-of-quality. As Exhibit SB-1 shows, Juran's model of optimum quality costs presents a concave function for total quality costs. As voluntary expenditures on appraisal and prevention increase, however, the increased conformance (lower defect rate) leads to lower involuntary failure costs. The minimum total quality cost occurs where the *marginal cost of prevention and appraisal* equals *the marginal cost of failure*.

The earlier cost-of-quality model, which reported only abnormal loss, provided no information on how to reduce this loss. However, the classification and cost-of-quality model shown in Exhibit SB-1 (Juran's model) makes it clear that to reduce total quality costs, appraisal and prevention activities (costs) must increase.

Exhibit SB-1. Juran's Model for Optimum Quality Cost



of quality at or below 2-mm variation, RV Company could no longer rely on detection of out-of-specification parts (or subassemblies). Instead, the company had to emphasize *prevention*—that is, it had to eliminate the root causes of variation as soon as problems were detected.

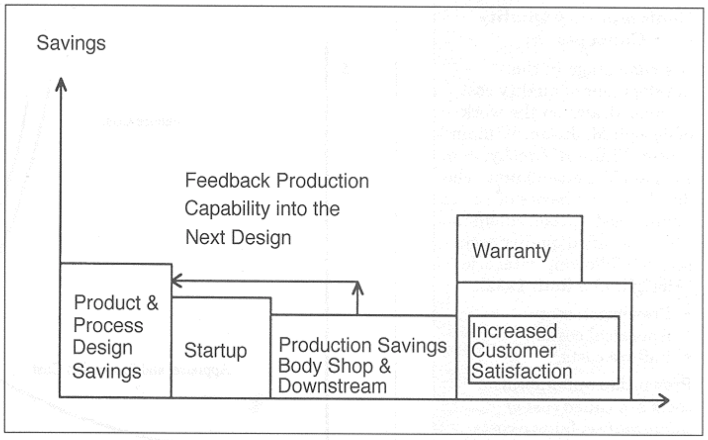
Quantification of Benefits

Cross-functional teams at RV Company eliminated the root causes of variation to world-class levels. Exhibit 2 depicts the expected life-cycle benefits from reduced variation in the body shop. Reduced variation and "centering of process means" lead to the following benefits:

- Reduced time and lower costs for start-up (launch).
- Reduced operating costs (both within the body shop and downstream).
- Less downtime and increased throughput.
- Lower warranty costs.
- Improved customer satisfaction.

Further, an assessment of the improved production process capabilities can be fed back into the next design. This feedback for improvements in the design of a company's processes and products is critically important.

Exhibit 2. Life Cycle Savings From Reduced Variation



Scrap and Rework

Most variation problems lead to scrapped or reworked subassemblies.

Most variation problems lead to scrapped or reworked subassemblies. High material and direct labor costs can easily be incurred if variation problems are not detected soon and the root causes resolved. RV Company's experience validates current thinking that for high-volume production, it is more economical to stop production and fix variation problems than to depend on inspection to find defective units and then scrap or rework them.

The savings from lower rework costs at RV Company cannot be separately computed using currently available historical data (people were assigned to rework as needed). Nonetheless, the savings are real and substantial, and they are included as part of the total reduction in labor costs. In other settings these savings may be estimated by keeping track of employees assigned to rework and overtime costs in rework.

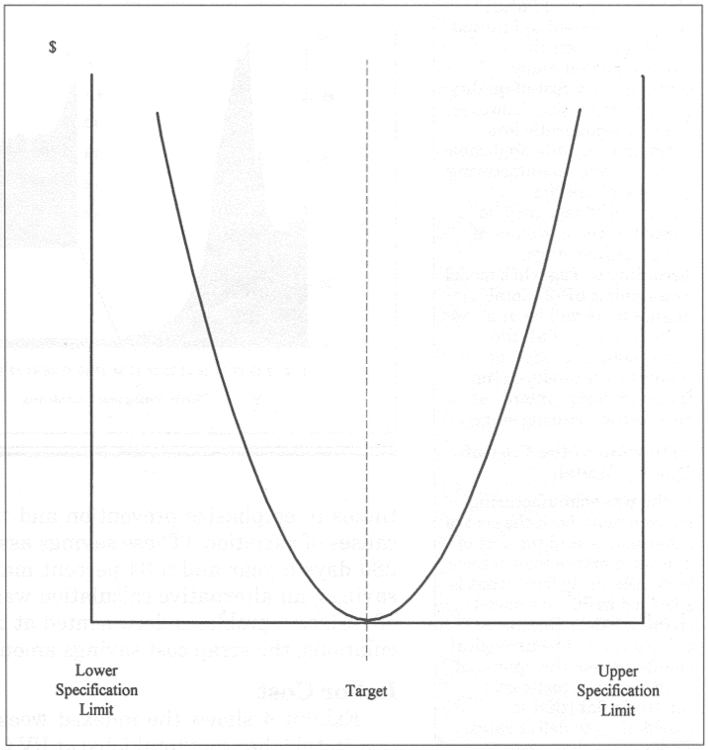
As problem-solving efforts stabilize a production process, the number of units requiring rework declines. Further, with 100 percent in-line measurement at several critical stages of the process, defects in later stages of production are not compounded by defects in earlier stages. Thus, the required rework is easier and takes less time.

Reduction in variation leads to higher quality; higher quality means fewer defective units and lower spoilage and rework costs.

Lean Production

Lean production systems at Toyota assign little space to rework and, in fact, perform almost no rework. By contrast, many mass-production plants devote as much as 20 percent of their plant area and 25 percent of their total hours to rework (Womack, Jones, and Roos, 1991). At RV Company, the rework areas are small and rework activities few. Currently, rework accounts for less than 4 percent of the total direct labor hours at RV Company.

Exhibit SB-2. Taguchi Loss Function



Characteristics of Juran's Model

Careful analysis of the cost-of-quality model in Exhibit SB-1 reveals several problems. Juran's model suggests that the optimal level of quality cost occurs at less than 100 percent conformance. The model depicts an increasingly steep appraisal and prevention cost curve, in accordance with the classical economic theory of diminishing marginal returns relative to reductions in defective output.

The general nature of the cost curves appears reasonable, but the exact shape of the cost curves has not been empirically determined because of difficulties in measuring many of the costs involved. The model is based on the traditional "pass/fail" model of quality. Under this approach, all products or parts considered "good" are assigned equal value for quality, even though one product or part may fall just within the tolerance limit while another may match the target value exactly.

Taguchi's Contribution

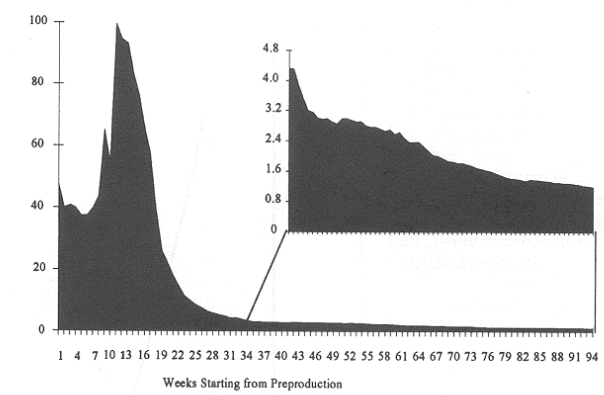
The Japanese quality guru Genichi Taguchi believed that there is virtually no advantage to shipping a product that barely meets quality control specifications over a product that fails. He exhorted manufacturers to get "on target" rather than trying just to stay within specifications (Taguchi and Clausing, 1990). According to Taguchi, a product that barely meets specifications is likely to fail, which could cause the loss of that customer—and perhaps others as well. (continued)

Similarly, scrap costs per unit (job) at RV Company have declined significantly since the late phase of preproduction (often called "total tryout"). Exhibit 3 presents the indexed cumulative average scrap cost per week (total scrap/total units) since preproduction began.

Average scrap cost per unit at RV Company was as high as 80 when the program began, but problem-solving efforts reduced the scrap cost by the beginning of first-shift production to about 4.4 per unit. This rapid reduction in scrap cost per unit was made possible mainly because of the successful use of in-line measurement systems. The current cumulative average scrap cost is about 1.2. The inset in Exhibit 3 shows this reduction in average scrap cost since the start of first-shift production. (*First-shift production* means that production takes place in one eight-hour shift. *Second-shift* indicates the time when the production level increases and a second shift is added. Thereafter production takes place in two eight-hour shifts.)

At the specified production level, the reduction in the average scrap rate amounts to an average after-tax savings of at least $550,000 per year—savings that are possible only if the system con-

Exhibit 3. Reduction in Average Scrap Cost



Taguchi emphasized losses that occur after a product is shipped (external failure costs) as opposed to internal failure costs, which traditional and many contemporary cost-of-quality models emphasize. However, Taguchi's quadratic loss function is equally applicable to multistage manufacturing systems where the subsequent stage may be viewed as the customer of the preceding stage. According to Taguchi's model (see Exhibit SB-2), total quality costs will be at a minimum only if all the parts, subassemblies, or products are produced "on target or design intent" at each manufacturing stage.

Extension of the Cost-of-Quality Model

In the new manufacturing environment, both the cost of conformance and the cost of nonconformance may behave very differently from what is specified in Juran's model (Exhibit SB-1). Recent behavioral and technological changes make the appraisal (conformance) cost curve relatively flat (that is, insensitive) to defect rates. This means that with empowered assembly line workers and automatic, 100 percent in-line laser gauging systems, appraisal costs do not change much whether the system measures all or only a few of the units produced.

By contrast, the cost of non conformance may be prohibitive. In a quality-based competitive environment, a company may rapidly lose market share and suffer huge losses if its products fail to meet the heightened quality expectations of customers.

The likely quality-cost behavior shown in Exhibit SB-3, however, is transitory. The total quality costs never reach a minimum below 100 percent conformance level (Diallo, Khan, and Vail, 1995).

tinues to emphasize prevention and timely elimination of the root causes of variation. (These savings assume two eight-hour shifts for 280 days a year and a 34 percent marginal tax rate. To verify the savings, an alternative calculation was made based on the 52 cases of variation problems documented at the plant. Based on these calculations, the scrap cost savings amounted to $748,000.)

Labor Cost

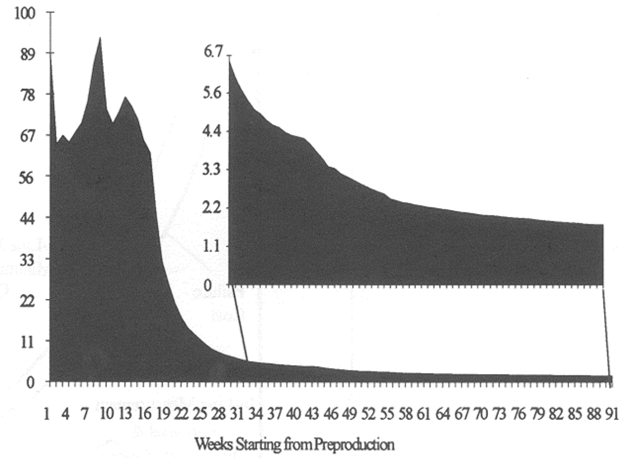
Exhibit 4 shows the indexed weekly cumulative average labor cost (total labor cost/total jobs) at RV Company since preproduction. The exhibit clearly shows the dramatic reduction in average labor cost from a high of more than 89 to about 6.4 at the start of first-shift production.

The inset in Exhibit 4 shows the reduction in average labor cost since the start of first-shift production. From week 34 to week 91, average labor cost decreased from 6.4 to 1.8. The effect of the learning in all the activities at the assembly plant is significant. Assuming no learning had occurred since the start of first-shift production, the total labor costs at the end of week 91 would be $94 million higher. The average after-tax savings from learning amount to about $30 million. (An alternative labor cost savings computation based on the actual reduction in the indexed weekly average cost yields more than $6 million in average after-tax savings.)

Other Manufacturing Expenses

Exhibit 5 shows the indexed weekly cumulative average of other manufacturing expenses, or OME (total OME/total jobs) since the start of preproduction. The inset in Exhibit 5 details the average OME—which was also reduced substantially—since the start of first-shift production.

Exhibit 4. Reduction in Average Labor Cost



The average annual after-tax savings in OME since the start of first-shift operations at RV Company amount to about $600,000 (based on standard jobs per hour, two eight-hour shifts, 280 days of operations, and a 34 percent marginal tax rate).

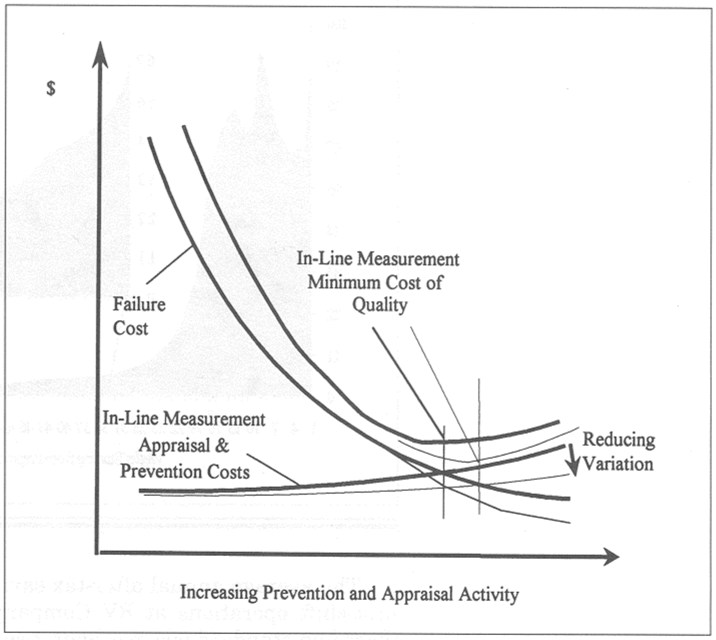
Work-in-Process

The ability of RV Company's in-line measurement system to provide data for process control in real time led to much better process control and to a more stable process. In a stable process, planning is easier and more accurate, so work-in-process (WIP) buffer inventories are kept to a minimum. Consequently, the lean production system operating at RV Company is more amenable to just-in-time (JIT) inventory systems.

Unfortunately, it is impossible to quantify the impact on inventories from reducing variation because RV Company was already using JIT. However, the effect of reduced variation on inventory levels is clear. The smooth, stable process that results from eliminating the root causes of variation helps RV Company achieve the ultimate goals of JIT, including near-zero inventory. In assembly plants that do not focus on variation reduction but have implemented JIT inventory system by management fiat, production stoppages usually happen often because of stockouts of WIP buffers.

At RV Company, an auto body assembly that is kept available to replace a defective assembly is a *clone*. Data on clones permit the savings from reduced WIP inventory to be estimated. At one time, RV Company had 12 clones at the "body-complete" stage; now there

Exhibit SB-3. Reductions in Cost-of-quality Through Reduced Variation



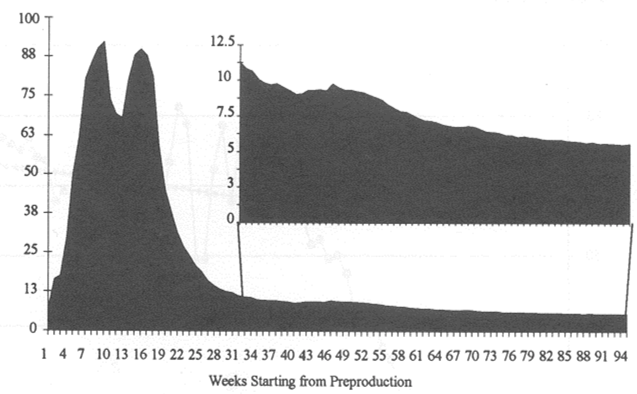
are only four clones. Although the $4,000 after-tax savings from the reduced investment in clones seems small, the potential savings are much greater. When engineering changes or product modifications occur, all clones must be scrapped and replaced. Therefore, the more clones, the higher the scrap and replacement cost.

Shorter Launch Time

Solving variation problems quickly leads to faster stabilization of a process. This, in turn, reduces the average launch time. A shorter launch time reduces the cost of introducing new models, and it also means additional contribution to profits because of increased output.

RV Company successfully completed a launch two weeks faster than the normal launch time. The two-week reduction resulted in after-tax savings of $660,000. (This calculation is based on the cost of operating one shift per day, excluding capital investment.) Completing a launch two weeks early means producing additional cars for sale, which (on an after-tax basis) contribute more than $8 million to profits (assuming one shift production per day, five days a week, and an estimated contribution of $4,000 per car). However, the additional contribution would depend on the concurrent readi-

Exhibit 5. Reduction in Other Manufacturing Expenses



ness of other areas or systems of the company. Even so, early availability of product from the body shop makes it possible for downstream systems to test earlier, thus shortening the overall launch period.

Less Downtime and Increased Throughput

A focus on reducing variation and centering process means on design intent means less downtime. RV Company is in an enviable position of being able to sell all the automobiles it can produce. The higher uptime translated into higher production (throughput) and sales. Increased sales from higher throughput means additional contribution toward covering fixed costs and generating profits. Said another way, higher uptime reduces costs through less overtime and other plant costs.

Increased sales from higher throughput means additional contribution toward covering fixed costs and generating profits.

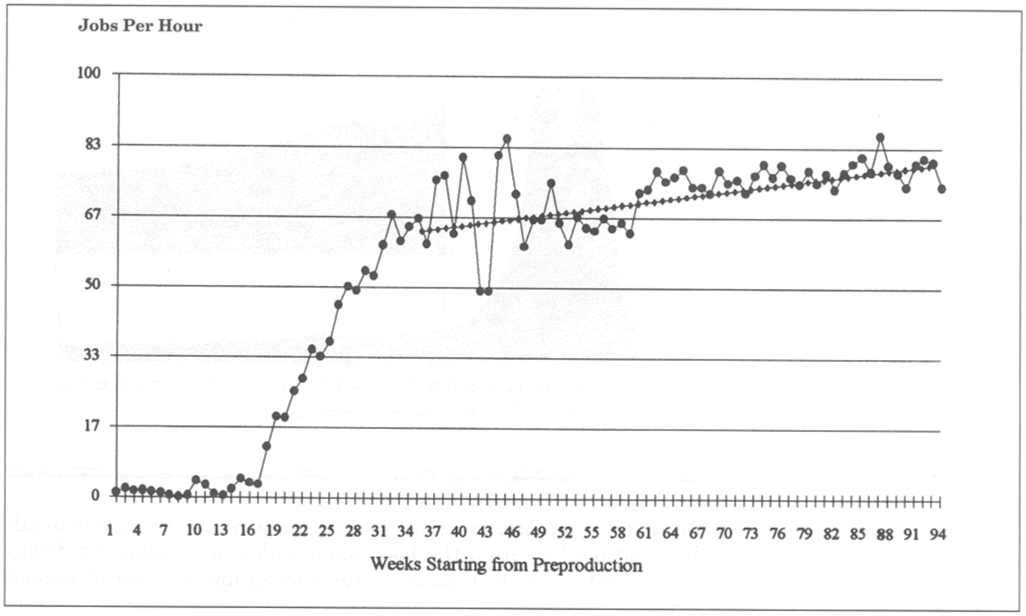
The additional contribution from increased throughput can be substantial. An increase in throughput of one unit per hour per shift can provide an annual after-tax contribution toward profits of more than $11 million (assuming that other areas of RV Company can follow through with the increased throughput). The throughput at RV Company has steadily gone up since launch.

Exhibit 6 shows the indexed jobs per hour (JPH) since the start of preproduction and the trend since the start of first-shift production. The JPH rate has risen by about 26 percent since the start of first shift, an average weekly increase of about five units. Thus, the additional after-tax contribution from more uptime is more than $59 million.

Higher Quality and Lower Costs

As Deming and Taguchi both maintained, managing variation is the key to quality improvement and cost reduction. The reduction

Exhibit 6. Indexed Jobs Per Hour



at RV Company was accomplished by means of continuous improvement and substantial investments in new technology, including a laser-based, 100 percent in-line measurement system.

Continuous Improvement

RV Company successfully reduced variation by establishing cross-functional teams that focused on solving variation problems and eliminating their root causes. RV Company has successfully reduced the variation of auto bodies to the original world-class goal of 2 mm. The automobile that RV Company builds is highly successful with customers and is in great demand.

Since the start of first-shift production, RV Company has significantly reduced its scrap cost, total labor cost, and OME. At the same time, a significant increase has occurred in the incremental contribution toward profit because of shorter launch times and increased uptime.

New Technology

Unfortunately, computing the return on the laser-based, 100 percent in-line measurement system is not easy. If only one percentage point of learning for labor cost savings is assigned to the in-line measurement system, the resulting average after-tax annual savings in labor cost assignable to the equipment is more than $3.5 million (compared to the approximately $2 million that the equipment cost). To truly isolate the effect of the in-line measurement system would require comparing the same overall system with and without the in-line measurement component. Unfortunately, this is not practicable.

Benefits

To summarize, the financial analysis shows the following benefits since the start of first-shift production:

- The moving-average scrap rate ($/job) declined by about 71 percent, for an estimated average after-tax savings of about $550,000.
- The moving-average labor cost declined by about 73 percent, for an estimated average after- tax savings of about $30 million.
- OME declined on a cost-per-unit basis by about 50 percent, for an estimated average after-tax savings of about $600,000.
- One type of WIP (clones) was reduced from 12 to 4, for an estimated reduction in investment of about $4,000.
- Launch time was reduced by two weeks, for an estimated after-tax contribution of more than $8 million.
- The number of units produced steadily increased by about 26 percent, for an estimated after-tax contribution of about $59 million.

Conclusion

Reducing variation leads to improved quality, which has a favorable effect on profits because of reduced costs and increased revenues. Overall costs are reduced by the following:

- Quicker responses to variation problems.
- Lower production costs in the body shop.
- Lower inventories.

Additional savings may be realized because of the following:

- The possibility of lower downstream costs.
- Higher-quality parts from suppliers who have implemented a variation reduction program.
- Lower worker environment costs (e.g., health care, injury, and accident) due to less complicated procedures and fewer occasions for manual interventions.

Revenues increase because of lower variation, higher throughput, higher employee satisfaction (easier work environment and pride in product), and higher customer satisfaction.

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