CHAPTER 72

TOTAL QUALITY MANAGEMENT AND THE MECHANICAL ENGINEER

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72.1 WHAT IS TOTAL QUALITY MANAGEMENT?

72.1.1 The Traditional Approach to Quality

Before considering a definition of Total Quality Management, for contrast let's review the traditional approach to quality. During the Industrial Revolution, a major change that allowed manufacturing to achieve significant efficiency gains was a division of labor for all aspects of manufacturing work. This approach, led by Frederick W. Taylor, advocated management of factory work by dividing it into simple, repetitive tasks that could be executed quickly and easily with a minimum of skill.

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Generally, Taylor's approach worked well for the time, making durable consumer items affordable for many.

During World War II, the Department of Defense pressed for a similar specialization in the quality function as a means to assure the quality of war materials. The government's document for quality, MIL-Q-9858, specified a separate and independent quality department with the responsibility to plan, audit, and assure that required quality levels were met. Usually, outgoing quality levels were met by significant amounts of inspection and test of the final product. Goods or services that did not conform to requirements were made to conform (reworked) or scrapped. Other documents, such as MIL-STD-105, specified how to sample and what decisions to make, based on the results of inspections. Commercial firms have often followed this organizational approach, some even adopting government inspection standards.

The practical effect of this organizational approach, as shown in Fig. 72.1, was to make the *quality* of the finished goods or services the *responsibility* of the quality department. There was little incentive for any other operation in the company to be concerned with quality. After all, the quality department *was* the department paid to find and fix defective goods or services.

By Frederick Taylor's logic, this arrangement still made sense. Quality engineers could improve their ability to plan for quality, develop inspection and test plans, and direct inspection staff. However, this was one area where division of labor and separation of responsibilities did not prove to be the most efficient approach for the entire enterprise, especially as products and services became more and more complex. First of all, inspection, particularly visual inspection, is never 100% successful in catching defects. As a result, there were still dissatisfied customers and warranty costs, even with significant levels of inspection. Second, it became apparent to some far-sighted business leaders that inspection and test were not adding value, but businesses were in fact supporting an entire "hidden factory" of extra floor space, materials, labor, and machinery to take care of rework and scrapped material. Some organizations paid lip service to the concept that "quality cannot be inspected into" the product, but few made an attempt to change. Those that did began to grasp the fact that the quality of goods and services, as perceived by the customer, is a function of the entire enterprise. Hence, the entire enterprise must be engaged in planning for quality and delivering quality results. As suggested in Fig. 72.2, it will take a different organizational approach to answer the new quality requirements.

72.1.2 The New Paradigm of Total Quality Management

This insight leads to a review of Total Quality Management (TQM). First, here is a definition of TQM for discussion purposes: "Total Quality Management is an evolving management philosophy and methodology for guiding the continuous improvement of products, processes and services with the objective of realizing optimum customer value and satisfaction. It fosters the engagement of everyone in the enterprise toward this end."[1] As is evident from the definition, TQM departs from the division of labor theory of Taylorism to assert that what the customer perceives as quality is the responsibility of everyone in the organization. This doesn't mean that the assembler of the engine is responsible for the finish on the hood of the car. The tools of TQM include methods to deploy and measure appropriate quality characteristics for each operation in the organization.

72.2 DEFINITIONS OF *QUALITY*

Several definitions of *quality* have been used over the years. Following are some of the predominant ones.

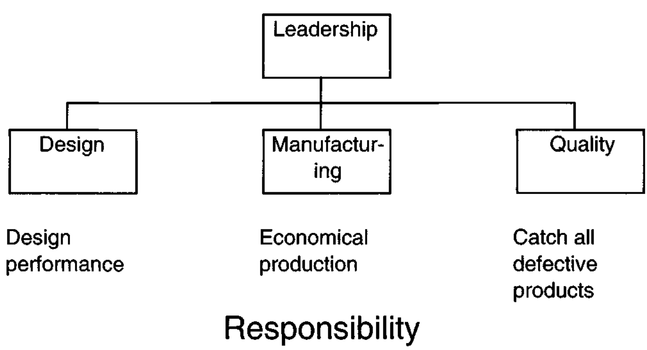
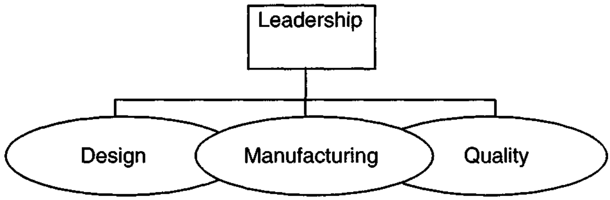


Fig. 72.1 Who has the responsibility for quality?



Design recognizes the responsbility to produce a design that can be manufactured economically.
Manufacturing recognizes the responsibility to develop stable processes and maintain control.
Quality audits products and systems to foster continuous improvement.

Fig. 72.2 A unified approach is needed.

- Freedom from defects[2]
- Fitness for use[3]
- The totality of features and characteristics of a product or service that bear on its ability to satisfy given needs[4]
- The features and characteristics that delight the customer[5]

A review of these definitions will show a progression from a narrow consideration of the absence or presence of defects to a more holistic consideration of the ability of the product or service to *satisfy* the customer. This progression parallels the evolution of quality management from just the management of inspection to TQM.

72.3 WHAT ARE THE BENEFITS FOR MY COMPANY?

There are several benefits stemming from the adoption of an active and effective TQM program. These include:

- Improved customer satisfaction from better products and services
- Improved profit margins from reduced costs
- Easier introduction of new products and services
- Higher worker satisfaction due to involvement with improvement teams, integrated product and process development teams, and design for manufacture and assembly (DFMA) teams

These are strong claims, but they can easily be supported by data. The first study to address the effects of TQM application beyond the quality of products and services was conducted by the General Accounting Office (GAO) at the request of Congressman Donald Ritter (R—Pa).[6] This study looked at 20 companies that received a site visit for the Malcolm Baldrige National Quality Award (MBNQA) (see Chapter 73) in 1988 and 1989. To receive a site visit for the MBNQA indicates that the company is a "finalist" in this assessment of TQM applications.

The GAO study considered data (where available) in four broad areas with a number of specific elements in each: (1) employee relations, (2) operating procedures, (3) customer satisfaction, and (4) financial performance. In each case, the available companies' data were analyzed for trends from the time the company reported it started its TQM initiatives. In addition, the companies' data were compared with metrics available from their specific industry. The results are shown in Fig. 72.3. All charts are to the same scale, represent average annual percent improvement, and have the results stated so that a positive bar represents a favorable result for the company. The specific elements for each area are printed under the bar.

In the area of employee-related indicators, the survey looked at employee satisfaction (from surveys), attendance, turnover, safety/health (lost work days due to work-related injury and illness), and suggestions received. These measures show the degree of personnel engagement in TQM and staff response to the initiative.

The survey also looked at operating indicators. These are metrics of the quality and costs of products and services. The categories of measurements included (1) reliability, (2) timeliness of

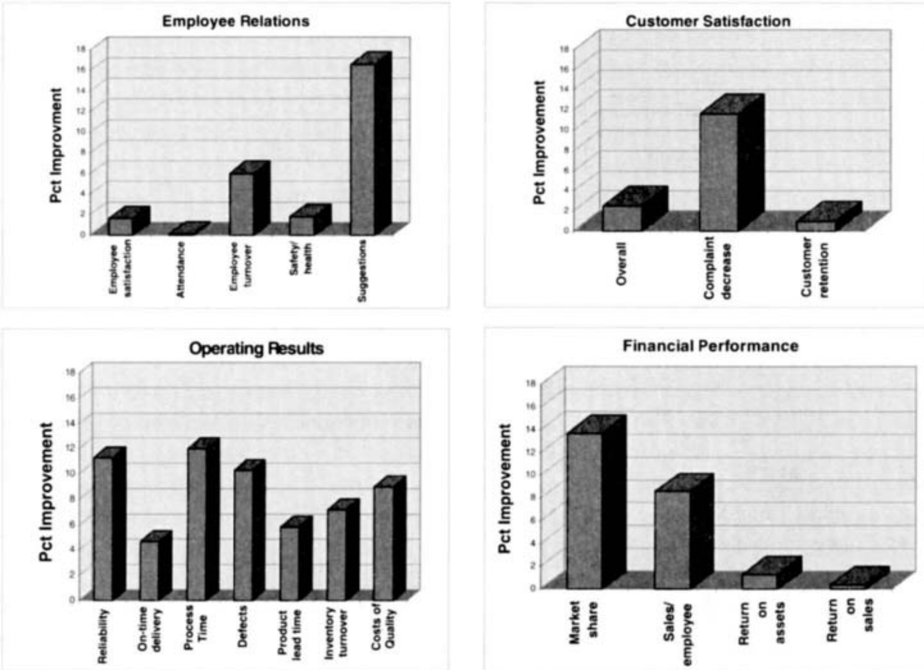


Fig. 72.3 Charts of results from the GAO TQM study.

delivery, (3) order-processing time, (4) errors or defects, (5) product lead time, (6) inventory turnover, (7) costs of quality, and (8) cost savings. These metrics are an expansion of "traditional" quality measures. They represent a measure of quality system effectiveness.

Customer satisfaction is a very important indicator for any business. If customers are not satisfied, the company's profitability will be affected at some point, usually sooner than later. This survey looked at three measures of customer satisfaction: (1) overall customer satisfaction, (2) customer complaints, and (3) customer retention.

The survey looked at the increased financial performance of the companies applying TQM. The metrics looked at were (1) market share, (2) sales per employee, (3) return on assets, and (4) return on sales. These measures put to rest the theory that TQM efforts do not offer an attractive return on investment. How much is a 14% annual increase in market share worth to your company?

72.4 HOW WILL IT CHANGE MY ROLE?

72.4.1 As a Mechanical Engineer

Traditionally, engineers become engineers because they have an aptitude for or prefer to deal with data and things. The typical mechanical engineer is most focused on one key responsibility, the performance of his or her design or process. This is still an important consideration, but as your organization adopts TQM, whether due to customer requirements or competitive pressures, some new dimensions will be added to your role. As shown in Fig. 72.4, TQM has many aspects that affect both the organization and the individuals. This section will include a brief discussion of some of them.

First of all, a mechanical engineer working in a TQM environment will probably be part of a multifunctional team, usually an integrated product and process development team (more on this will be found in a later section of this chapter). This will require what may be new skills, such as listening to other viewpoints on a design, reaching consensus on decisions, and achieving alignment on customer needs. To the mechanical engineer, teams may appear inefficient, slowing down "important" design work, but the performance of a well-developed team has often proven superior to other organizational forms.

Another change that a mechanical engineer may note in TQM is a focus on processes. In the past, engineers usually felt that the result was important, not necessarily the means. TQM focusses on the means (processes) as much as the results. This is one way to achieve minimum variation in

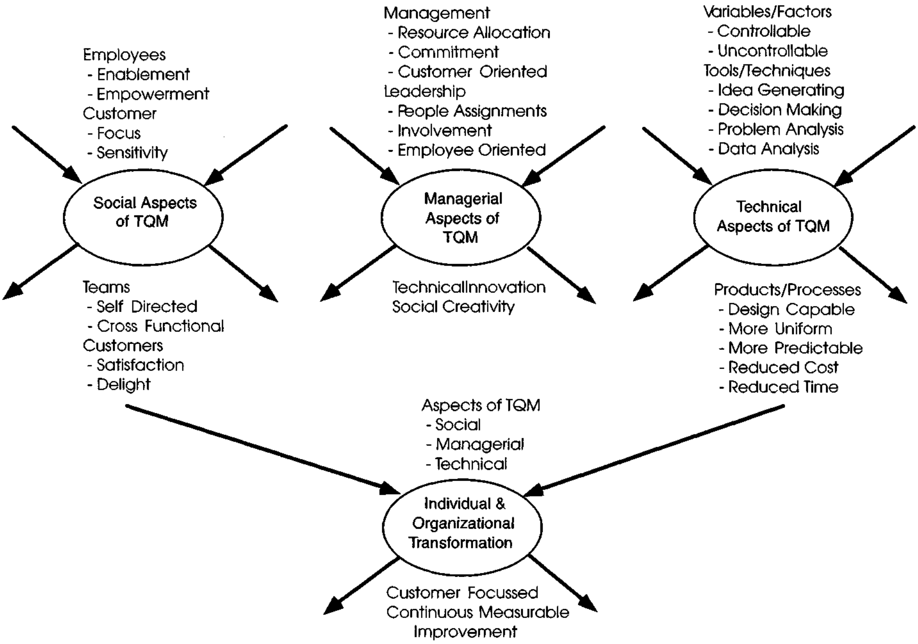


Fig. 72.4 The comprehensive model of TQM.

results, to consistently use the best process available. At first thought, this may appear restrictive, but it is not. TQM is serious about continuous improvement. This means that processes will not remain static, but when the current "best process" is discovered, all functions that can use it are expected to use it.

A final key change that a mechanical engineer might note in an organization adopting TQM involves the engineer's relationship with the management structure. To free up the creative capability in the organization and to make it more agile, management must move from a directive relationship to a coaching or guiding relationship. Of course, this will be a significant change for the manager and engineer and sometimes the transition is not smooth.

72.4.2 As a Manager of Mechanical Engineers

If you are a manager of mechanical engineers in an organization deploying TQM, you will be in for changes that may make you feel insecure in your position. You will see a drive to reduce your apparent authority, to place your staff on teams, and to turn your position into that of "coach." It's possible that you'll stop receiving funding to supply personnel for projects. Instead the funding will go directly to the team. Your personnel will most likely be located with their team, perhaps geographically removed from you.

We have emphasized this negative picture to draw attention to the focus on management in TQM. A significant part of the pressure to change and the pressure from change falls on management. If you think that TQM is something to assign to someone or something that staff can do without your involvement, you are on a path to a failed implementation.

In addition to the personal considerations, there are other concerns that you must consider for a TQM implementation.

- Does your organization have a plan for identifying what teams, how many are needed, and how you will task them?
- Do you have a way to assign team leaders and team members?
- How are you going to equip teams with the TQM tools and team skills to succeed?
- Do you have subject matter experts (SMEs) identified for TQM tools and team skills?
- Do you currently have data systems on your processes?
- Do you know what your customers expect?
- How will you fund the teams?

- If the funding goes to the teams, how will you know what staffing levels to maintain?
- How will you evaluate and help your personnel develop if they are on a team, especially if they are geographically separate from you?
- How will you know when a team is not performing?

72.5 WHAT ARE THE TOOLS OF TOTAL QUALITY MANAGEMENT AND HOW DO I USE THEM?

72.5.1 Technical Tools—Quality Function Deployment (QFD)

QFD is the first of the "major" tools of TQM we will discuss. By "major" we mean that the tool fulfills a major need in a TQM application, it possesses a fairly extensive research and literature base, and there are no more efficient or effective alternatives.

If *quality* is defined by the customer, QFD is the tool to assure that the customers' *vision of quality* is captured, defined, deployed through the enterprise, and linked to the activities of the enterprise. A few of the benefits stemming from the use of QFD are:

- More satisfied customers
- Greater product team linkage and alignment
- More efficient use of resources, since the team works on the "important things first"
- The ability to present and evaluate data on requirements, alternatives, competitive position, targets, possible sources of interrelations, and priorities

QFD was initially applied in the 1960s in Japan. It was developed by engineers and managers in the Kobe shipyards of Mitsubishi Heavy Industries, and it was refined through other Japanese industries in the 1970s. QFD was first recognized as an important tool for use in the United States by Dr. Donald Clausing (formerly of Xerox, now at MIT). It was translated into English and introduced to the U.S. in the early 1980s. Following publication of the first book on the subject, *Better Designs in Half the Time,*[5] it has been applied in many diverse U.S. situations.

At the heart of applying QFD are one or more matrices. These matrices are the key to QFD's ability to link customer requirements (referred to as the *voice of the customer* or *customer WHATs* in QFD literature) with the organization's plans, product or service features, options, and analysis (referred to as *HOWs*). The first matrix used in a major application of QFD will usually be a form of the A-1 matrix (Ref. 5, pp. 2–6). This matrix often includes features not always applied in the other matrices. As a result, it often takes a characteristic form and is called the *House of Quality* (HOQ) in QFD literature. Figure 72.5 presents the basic form of the HOQ.

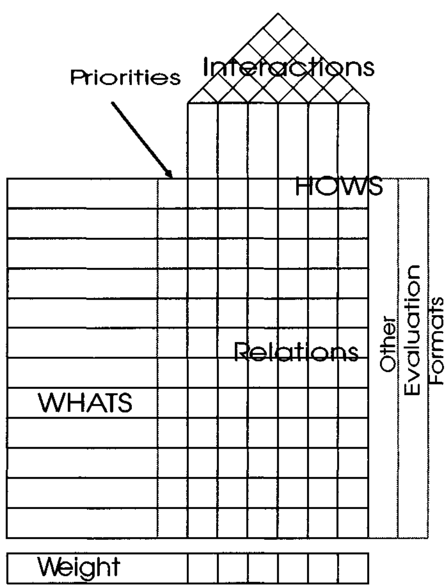


Fig. 72.5 The House of Quality (HOQ) and its major elements.

The A-1 matrix starts with either raw (verbatim) or restated customer WHATs and their priorities. The priorities are usually coded from 10 to 1, with 10 representing the most important item(s) and 1 representing the least. These WHATs and their priorities are listed as row headings down the left side of the matrix. Frequently we find that customer WHATs are qualitative requirements that are difficult to directly relate to design requirements, so the project team will develop a list of substitute quality characteristics and place these as column headings on this matrix. The column headings in QFD matrices are referred to as *HOWs* in QFD literature. Substitute quality characteristics are usually quantifiable measures that function as high-level product or process design targets and metrics. For example, a customer may want good gas mileage (a WHAT), but the design team needs to set a specific miles-per-gallon target (a HOW). Next the team develops a consensus on the correlation between the WHATs and the HOWs. Each correlation is marked in the row–column intersections using symbols having an associated numeric weight. The convention is 9 points for a high correlation between a WHAT and a HOW, with 3, 1, and 0 for medium, low, and no correlations, respectively. The assignment of points to the various correlation levels and the prioritization of customer WHATs are used to develop a weighted list of HOWs. The correlation values (9, 3, 1, and 0) are multiplied by the WHATs priority values and summed over each HOW column. These column summations indicate the relative importance of the substitute quality characteristics and their strength of linkage to the customer requirements.

The other major element of the A-1 matrix is the characteristic triangular *roof* (an isosceles triangle) which contains the interrelationship assessments of the HOWs. In many cases, improvement in one or more substitute quality characteristics may foster improvement in or be detrimental to others. These positive and negative interrelationships are noted in the column–column intersections of the roof. For example, if customer WHATs for a car include "good acceleration" and "economical fuel consumption," these may be translated into substitute quality characteristics (HOWs) such as the 0–60 mph time, time required to pass, and highway mileage (mpg). Subsequent design effort to improve the 0–60 mph time will likely improve the time to pass, but will also likely reduce the highway mileage. These would be reflected as positive and negative interrelationships, respectively.

Other features that may be added to the A-1 matrix include target values, competitive assessments, risk assessments, and others. These are typically entered as separate rows or columns on the bottom or right side of the A-1 matrix.

The key output of the A-1 matrix is a prioritized list of substitute quality characteristics. This list may be used as the inputs (WHATs) to other matrices. For example, in Fig. 72.6 we show the HOWs

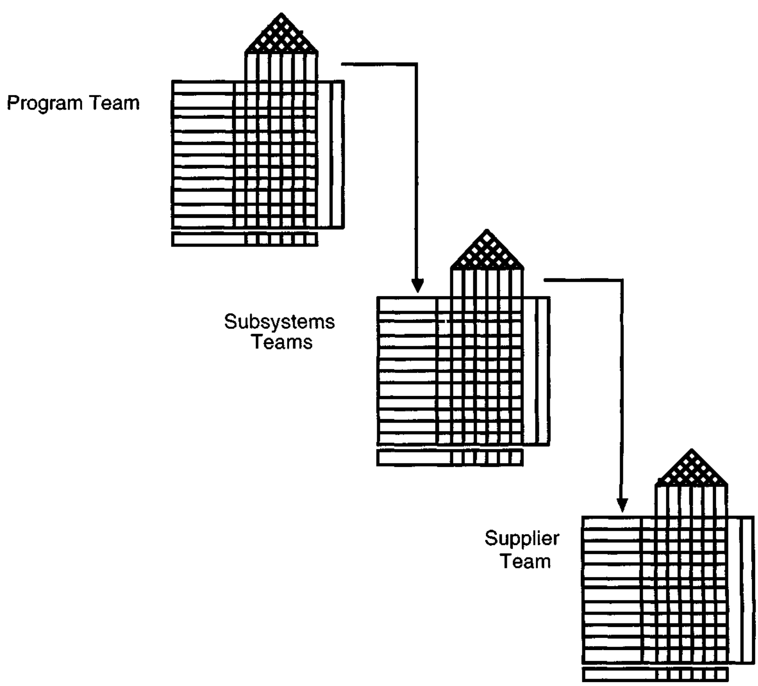


Fig. 72.6 QFD matrices may be used to "flowdown" customer requirements.

of the project A-1 matrix flowing down to become WHATs for subsystem teams. Their HOWs may then be flowed down as inputs (WHATs) for their suppliers. Following the car mileage example, target mileage requirements may be flowed to the engine team and efficiency requirements flowed to the transmission team. They may then break their requirements out to fuel injection, piston, gear, and any other suppliers. This assures that the *voice of the customer* is deployed throughout the enterprise and that all activities are linked with customer requirements.

72.5.2 Technical Tools—Seven Management and Planning (7 MP) Tools

Dr. Deming proposed that TQM applications should follow what is now known as the PDCA (plan, do, check, act)* cycle, as pictured in Fig. 72.7. The PDCA cycle is a logical approach that parallels the scientific method of "observe, hypothesize, test hypothesis, modify hypothesis." Most early TQM tools addressed the "do, check, act" portion of the cycle. In later years, a suite of tools were developed to assist the planning efforts of TQM. These have become known as the *7 MP* tools:[7]

1. Affinity diagram
2. Tree diagram
3. Prioritization matrix
4. Interrelationship digraph
5. Matrix diagram
6. Activity network diagram
7. Process decision program chart

The first tool widely used in the 7 MP suite is the affinity diagram, which is excellent for generating and grouping ideas and concepts. Teams will find the affinity diagram useful for exploring issues in a new project or factors to consider during implementation. This tool often uses simple sticky papers or cards to generate and collect team ideas. These are then arranged into "affinity" groupings by the team and assigned a descriptive header. The affinity header descriptions represent the key issues or concepts identified by the team. The number of cards under each header indicates the breadth of team consensus on the issue.

The tree diagram, pictured in Fig. 72.8, is a good tool to break down a complex project into manageable tasks. The team starts with the overall project or goal description, which is broken down into the next logical division of effort. Each new element may be further divided (if it makes sense) until the team has a list of self-contained tasks that may be assigned to one or more subteams or individuals.

A prioritization matrix is most useful to develop a prioritized list from a large set of options. This tool makes it easy for the team to focus on the important items and avoid "hidden agendas" that

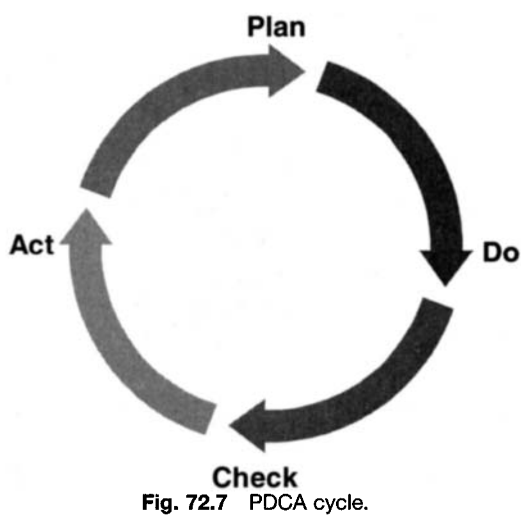


Fig. 72.7 PDCA cycle.

*Since early writings, Dr. Deming has modified this to PDSA—plan, do, study, act.

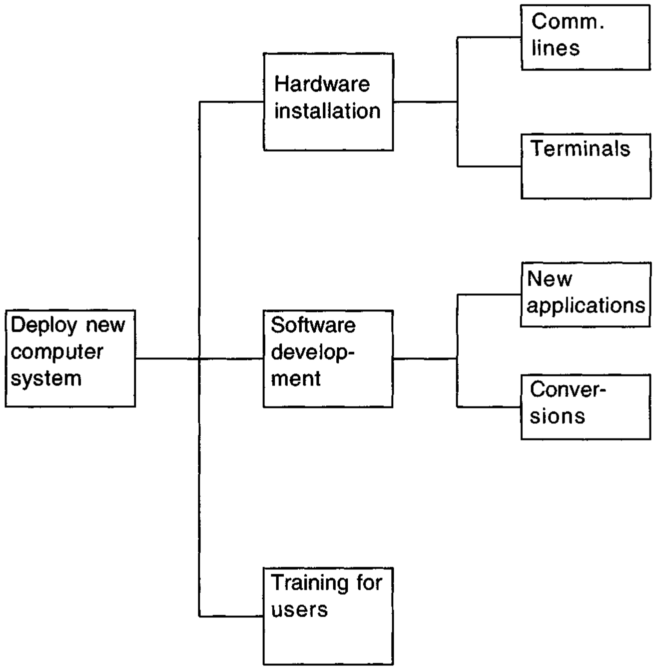


Fig. 72.8 Example tree diagram.

may drive the team. In this tool, the team uses pair-wise comparisons to determine the overall relationship of a large number of elements.

An interrelationship digraph (ID), as presented in Fig. 72.9, helps a team discover the relationships and dependencies between project activities. Using simple graphical techniques, the team indicates task relationships one by one. When all the pair-wise comparisons are completed, the team has the information necessary to identify the driver tasks (tasks that drive or precede a large number of other

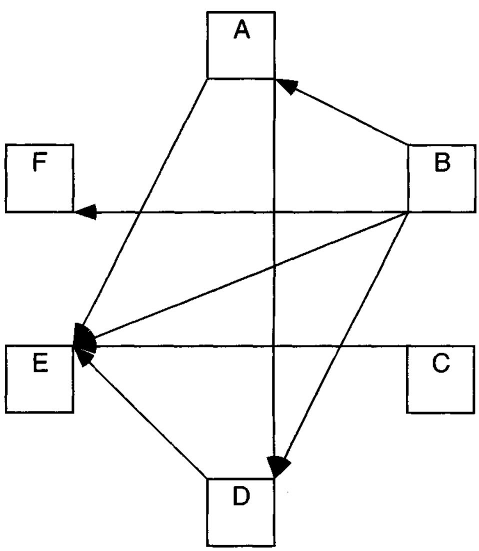


Fig. 72.9 Example ID (arrows represent influence or predecessor relations).

tasks) and the outcomes tasks (tasks that depend on a large number of other tasks). Driver tasks can be managed more closely to avoid schedule risk and outcome tasks can be monitored for project performance.

The activity network diagram (AND), portrayed in Fig. 72.10, is a way for a team to schedule project tasks. The team can use simple sticky notes or cards to list the program tasks. These can then be arranged in the anticipated flow order (sequential, parallel, or a combination) with directional arrows drawn between related tasks. The team can then assign times to each task placing the task process time on the paper or card. The result is an ordered diagram that can show predecessor/successor relationships, total task time, and the critical path. For those tasks not on the critical path, the team can calculate late start times based on the available slack time for that path. The information contained in an AND can be input to project-management software to develop the familiar Gantt chart.

Matrix diagrams allow a team to display relationships and responsibilities in a concise and efficient manner. At first glance this may appear similar to the ID, but matrix diagrams are most used for *assignments* not *assessments*. For example, a team may use a tree diagram to divide a project into manageable tasks and then apply a matrix diagram to assign responsibilities for the tasks. Matrix diagrams are related to QFD in their application approach.

The process decision program chart (PDPC), as described in Figure 72.11, is a tool that helps to develop contingency planning for the project. From the use of the previous 7 MP tools, your team should be able to develop a plan for your project. In the PDPC you can explore likely problems for each step. These may be graphically shown as a tree under each step. Contingency countermeasures can then be planned for each potential problem and the team then selects their best choice from the options.

72.5.3 Technical Tools—Design of Experiments (DOE)

A key responsibility of a mechanical engineer is to obtain the required performance from a system or component of a system. This usually requires simulations, trade studies, or experimentation with various system components and input parameters. Engineers are typically taught methods that require certain assumptions or apply approximations for the underlying system equations. For best performance, this may not be sufficient. Approximations may not be accurate enough and are singularly inadequate to guide variability reduction.

Design of experiments of DOE is the tool of choice for trade studies and system or component experimentation. A properly planned and conducted DOE will yield the most useful information possible from a series of experimental runs, giving the engineer not only the identity of key pa-

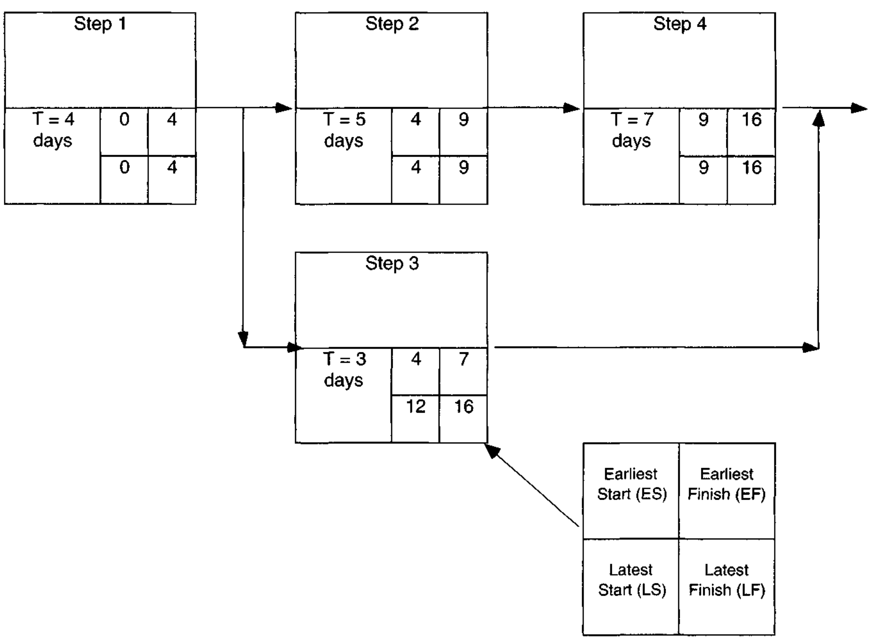


Fig. 72.10 Example activity network diagram.

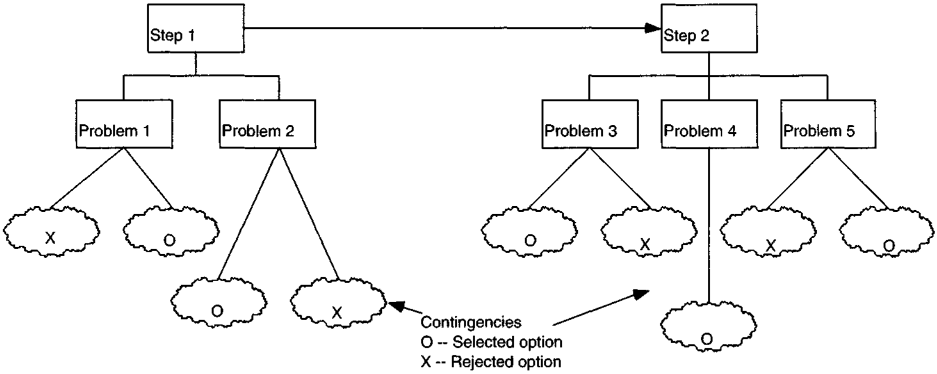
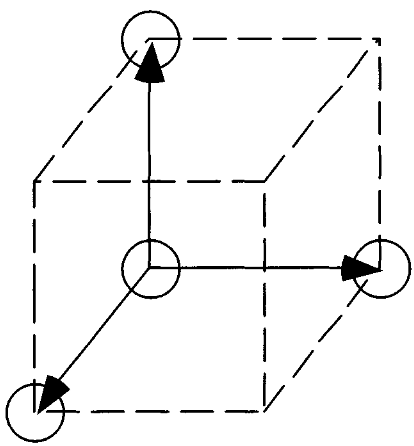


Fig. 72.11 Example process decision program chart.

rameters, but also an estimate of the underlying performance equation. This will allow the engineer to efficiently set the system up for optimum performance in nearly all cases.

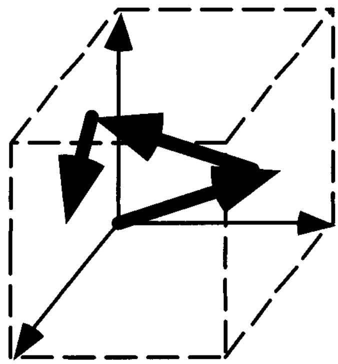
The chief competitor to DOE is one-factor-at-a-time (OFAAT) experimentation, where an engineer holds all but one factor constant. That factor is varied on one or more experimental runs to see if it has an effect on the system response. This is repeated for the other factors. Unfortunately, OFAAT leads to only linear, and usually only first-order, information on each experimental factor. If there are significant system interactions or higher-order effects, OFAAT will not reveal them. In Fig. 72.12, a system space is shown for a system with three factors, each at two levels. Experimenting through OFAAT will only explore the four points (circled in Fig. 72.12) where first-order information is available. If there is a significant two-factor interaction in the system, it will show at the appropriate corner point where both factors are changed. If there is a three-factor interaction, it will require information from the corner where all three factors are changed.

Another competitor to OFAAT is "random" experimentation, as displayed in Fig. 72.13. In this approach, a number of process factors are changed each time the experiment is done. With this



For a process with three factors at two levels, one factor at a time experiments explore only a limited part of the process domain. We will gain no knowledge of interactions with this approach.

Fig. 72.12 One-factor-at-a-time.



For a process with three factors, random change to all factors represents random movement in the experimental domain.

Fig. 72.13 Random experimental movement.

approach, if the process improves or grows worse, the team will not know which factor or factors were the influence.

In contrast to OFAAT and random experimentation, DOE systematically measures the system response as multiple factors are changed. The orderly and planned change of system factors is the key to DOE. Prior to the experiment, the engineer, often using a multifunctional team, will determine which factors (system inputs or parameters) might affect system response. The experimental levels (factor settings) for each factor will also be determined. Finally, the team should decide how much experimentation the project can afford. This and other preferences will determine the type of experiment to conduct.

There are many types of experimental designs. Generally, an experiment with more than one factor falls into one of the following major classifications:

- *Full factorial.* An experiment where all possible combinations of factor level settings are run at least once. If there are n factors, all at two levels, this will result in 2^n experimental runs for one replication. This type of experiment can explore the effects of all factors and factor interaction combinations.
- Fractional factorial. An experiment where only a specific subset of the possible factor level settings is run. If there are n factors, all at two levels, a half-fractional experiment will require 2^{n-1} runs for one replication. This experimental design reduces the number of experimental runs, but the cost is a loss of information, as interactions may be confounded with other interactions or main factors. Usually the design is structured so that higher level interactions (three-factor or higher) cannot be separated from the effect of another factor or lower-level factor interaction. In this type of experimental design, experience and knowledge are essential to avoid an experiment that mixes interactions unwisely.

There are several experimental methodologies that make use of these key experimental design types. Classical DOE, developed by Sir Ronald Fisher in England and promoted in the U.S. by Box, Hunter, and Hunter, uses both full and fractional factorial designs.[8] In the early 1980s, Dr. Genichi Taguchi began to promote in the United States an experimental methodology that uses special set of fractional factorial designs.[9] Although the experimental designs of Dr. Taguchi are not unique, his approach generated a dramatic increase in interest in DOE, especially among engineers. Dr. Taguchi made three major contributions to DOE. First, he developed a DOE methodology that offered clearer guidance to engineers than earlier approaches. Secondly, he promoted the concept of "robust design" and showed how DOE could be used to obtain it. Finally, he promoted the application of a quality loss function, expressed in dollars, showing how the enterprise, and society in general, are affected by variation from a target value.[10]

Usually experiments are run with factors at two levels. Occasionally an experiment deals with attribute factors (qualitative factors such as material types) at more than two levels. Sometimes nonlinear effects are expected, so even continuous factors (factors with settings on some continuous scale, such as temperature) are run at three or more levels.

72.5.4 Technical Tools—SPC, SQC, and 7 QC

One technical tool for TQM that came to early public attention was SPC (statistical process control). After somewhat rocky first application attempts, many companies are finding SPC to be useful for reducing defects, lowering defect rates, and making key processes much more consistent and dependable. The key to successful SPC application is understanding what SPC does and doesn't do.

SPC is the application of statistical (often in graphical form) methods to identify when a process may have been influenced by a "special" cause of variation. Dr. Walter Shewhart, who developed the earliest concepts and applications of SPC, divided process variation into two types. One type of variation he described is often called "common cause" or "normal" process variation in the literature. Normal variation results from the myriad of factors inherent to the process interacting with each other. Examples of normal process variation sources in a simple drilling operation include drill splay, variation in bits, variation in material, and so on. These factors interact and create a resulting pattern of variation in hole size, location, and so on. The second form of variation described by Dr. Shewhart is often referred to as "special cause" variation. Examples of special causes in the previously mentioned drilling operation might include changes in personnel, excess bit wear, changes in material clamping technique, changes in material, and so on.

We make the distinction between these sources of variation to separate the manageable from the unmanageable. Special causes of variation can usually be identified and removed from the process. Normal causes of variation can only be removed or reduced by changing the process, which often requires management involvement and/or capital expenditure. Although process changes may be necessary, usually removing special causes variation sources is more cost-effective and should be addressed first.

How does SPC fit into this? Dr. Shewhart, working in an AT&T Western Electric plant, saw that their processes had a lot of variation and that operators were constantly adjusting. He suspected that they were often reacting to normal variations and that their additional adjustments were adding to the process variation. He proposed the use of SPC and SPC charts to signal when a process may have been influenced by a special cause of variation. Then the operators, engineers, or managers could pursue adjustments or investigations, as necessary.

SPC charts come in many forms, but in general all plot one or more statistics (a descriptive measure from a unit or sample) on a chart that contains control limits, such as the chart in Fig. 72.14. The control limits are derived from past stable process data and usually represent $\bar{X} \pm 3s$ for each statistic (note that some statistics do not have a lower limit) where $\bar{X}$ is the long-run average for the statistic and $3s$ is three times the standard deviation of the statistic. If the statistic follows the normal distribution (and nearly all will, due to the central limit theorem), a point outside the control limit would only occur 0.27% of the time. Thus, a point outside either limit most likely reflects the influence of a special cause of variation. In addition to watching for points beyond the control limit, SPC practitioners also apply tests for patterns in consecutive points. Such patterns, such as trends of seven points in a row increasing or decreasing, also reflect events that would not likely happen in a process operating only with normal causes of variation. In Fig. 72.14, we see an $\bar{X}$ and R chart. In this chart, we plot sample averages ($\bar{X}$) and the range (R) for each subgroup. A subgroup usually consists of 2 to 10 samples for this type of chart. This type of chart detects both a shift in the process average and a change in process variation. Following are some rules for abnormal patterns in SPC charts:[11]

- One point beyond a control limit
- A run of seven or more points either up or down or consecutive above or below the centerline
- Two of three consecutive points outside 2 sigma, but still inside the 3-sigma line
- Four of five consecutive points beyond 1 sigma

While SPC deals with in-process measures, often our only significant way to measure the process result is by measuring the performance of the finished product. For example, when we assemble an electronic circuit, there are in-process measures to be monitored, but the final performance can only be measured by final test. As with in-process measures, final performance variation is a function of the variation resulting from normal and special causes. SPC can be used in this case to identify when to investigate for a special cause and apply corrective action. Often this approach is called *statistical quality control* (SQC). The same charts and approaches are often used. We should note that SQC should not be used as a substitute for SPC. Since SPC is directed at process inputs, not later in the cycle, it offers faster detection and correction of problems.

SPC and SQC are powerful tools, but they essentially do only one thing: they identify when a process was probably influenced by a special cause of variation. When that occurs, the team must

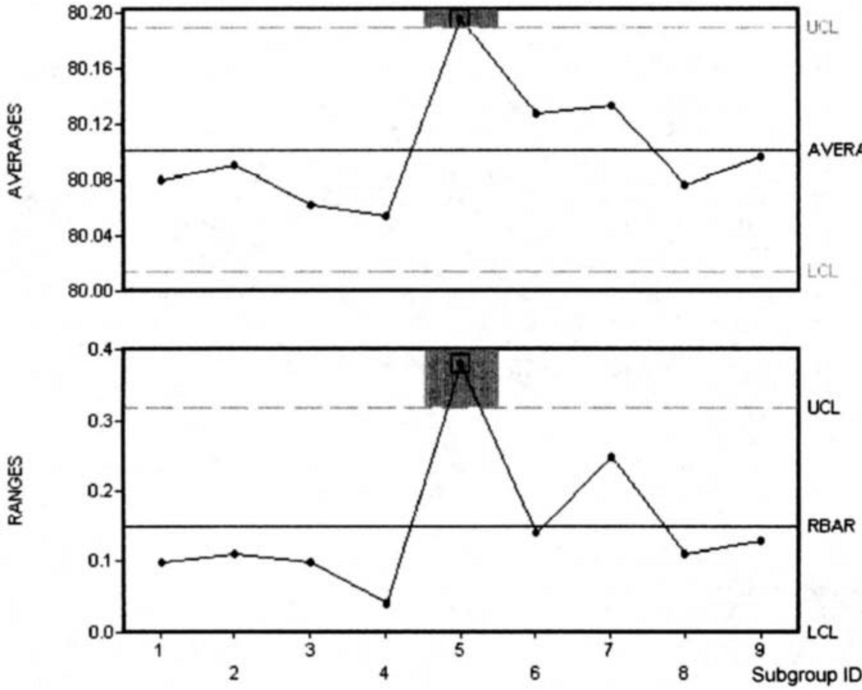


Fig. 72.14 Example *X* bar (*X*) and *R* chart (with one point out of control).

determine what happened and remove the cause to return the process to the normal state. Many of the tools for this job are grouped with SPC/SQC in what are called the *seven quality-control* (7 QC) tools:[11,12]

1. SPC/SQC
2. Histograms
3. Scatter plots
4. Pareto charts
5. Fishbone diagrams
6. Check sheets
7. Defect maps

Application of these tools with SPC will enable the team to maintain a stable process.

72.5.5 Technical Tools—Process Capability or Validation Studies

One of the more useful methodologies coming from TQM applications is the joining of manufacturing process capability assessment and the processes of developing design requirements. As was previously discussed, there have often been barriers between design and manufacturing. There was distrust, finger-pointing, and a general lack of teamwork.

For most companies, engineering design has been slow to recognize that they had a responsibility to work with manufacturing to develop a design package meeting customers' needs that was *manufacturable.* For their part, manufacturing has not been proactive in work to develop consistent processes with minimum variation. There is plenty of blame to go around, so how does an organization change? A key way to change without arguing is to look at facts and data. Characterize your processes according to what you expect of them (engineering requirements). Based on the results, you may decide that it is more cost-effective to change the design for some parameters if they appear to be controlled too tightly. If the design requires certain performance, but the current process can't reliably meet requirements, you must improve the process! Following are the steps for doing so. They are easy to follow.

1. Prioritize your processes and start working on the highest one(s), i.e., the vital few.
2. If the process doesn't have SPC, apply it!
3. Get the process under statistical control, i.e., predictable.
4. From the SPC chart, obtain estimates of the process average and standard deviation.
5. Assess the process C_{pk}.
6. Based on the C_{pk} and economic considerations, change the product specifications or improve the process to obtain C_{pk} goals.
7. Move on to the next process.

First of all, you should develop a strategy of work. Since you probably don't have resources to do everything, make sure you do the important things first. The next two steps are key. If you don't have SPC on the process, you can't determine if it's stable. If the process is not stable, all subsequent assessments will be worthless.

In steps 4 and 5, you obtain estimates of the process average and standard deviation and then apply them to an assessment of performance called the process performance index (C_{pk}). This measure (calculations and performance values are given in Fig. 72.15) shows how well three standard deviations fit between the process average and the closest specification limit. What value is appropriate? Many organizations use a C_{pk} of 1.33 as a minimum value. This means that four standard deviations fit in the distance between the process average and the closest specification. A few companies are using C_{pk} values of 1.50 as their target. Such higher values of C_{pk} allow more margin if the process shifts. You can see this in the values listed in Fig. 72.15 that show the effect of 1 and 1.5 standard deviation shifts.

The last two steps must not be ignored. If you find that the process capability is not acceptable, you must change the design requirements, improve the process, or *live with poor process performance for as long as you make the product.* The decision of which to address—design, process, or both—is an economic one. When you have completed this project, move on to the next one. One element of process assessment that should not be neglected is gage repeatability or reproducibility assessment. If the major source of process variation is in the measurement, it is usually the cheapest way to improve the process.

72.5.6 Technical Tools—Other TQM Tools

By some counts there are more than 100 TQM tools that may be applied for different aspects of TQM applications.[12] These range from simple graphical procedures for data exploration to complex tools like DOE. A partial list follows:

- Activity-based costing
- Bar chart
- Benchmarking
- Brainstorming
- Business process re-engineering
- Continuous improvement
- Cost of quality
- Critical path method (CPM)
- Cycle time management
- Data-collection strategy
- Defect map
- Delphi method
- Deployment chart
- Design for manufacture/assembly
- Events log
- Failure mode and effects analysis
- Fault tree analysis
- Five whys
- Gap analysis
- Imagineering
- Just-in-time
- Nominal group technique
- Policy deployment
- Problem solving
- Ranking
- Sampling
- Scatter analysis
- Spider chart
- Stratification
- Survey analysis
- Synchronous workshop
- Systems analysis
- Thematic content analysis
- Time study sheet
- Value engineering

72.5.7 Cultural/Social Tools—Concurrent Engineering

In the past, a new product-development effort followed a predictable path. Design engineers worked with marketing and customers on initial feasibility studies. If these studies looked favorable, one or more prototypes were then built, usually in a special prototype facility. An initial design was then formulated and a pilot production scheduled. During this time, manufacturing engineers were drawn

$$C_{pk} = \frac{\min\{USL - \bar{X}, \bar{X} - LSL\}}{3s}$$

$\bar{X}$ -- Process average
s -- Process standard deviation
USL -- Upper spec limit
LSL -- Lower spec limit

Cpk	Percent defective	Pct defective with 1 SD shift	Pct defective with 1.5SD shift
0	50.00%	84.13%	93.32%
0.33	16.11%	50.40%	69.50%
0.50	6.68%	30.85%	50.00%
0.67	2.22%	15.62%	30.50%
1.00	0.13%	2.28%	6.68%
1.33	0.00%	0.14%	0.64%
1.50	0.00%	0.02%	0.13%
1.67	0.00%	0.00%	0.02%
2.00	0.00%	0.00%	0.00%

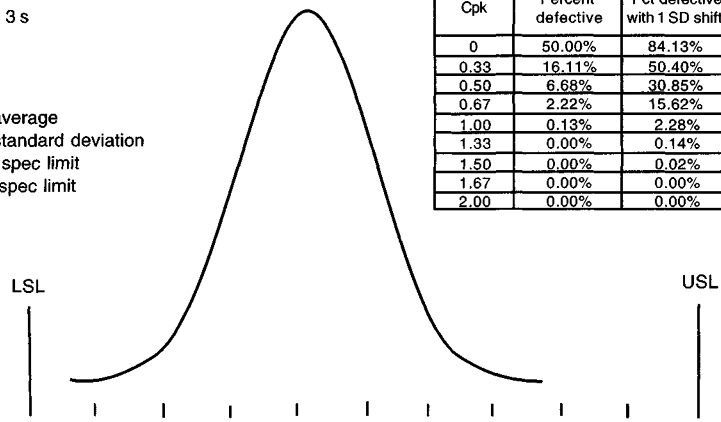


Fig. 72.15 C_{pk} formula and selected values.

into the project. At the same time, marketing's involvement was reduced, since the design group had their input and the project became a production problem. At this point, engineering changes increased as producibility problems and cost issues emerged.

As full-scale production begins, after-market support's involvement increases. Additionally, marketing often gets involved again with new input from early customers and competitive comparisons. Since the whole process may take some time, this new marketing input can represent a significant customer change in tastes and reaction to competing products. This adds to the engineering change rate. In many projects, the change rate may continue at a high level well into full-scale production. This phenomenon, described as the *engineering version of rework,* can be very significant in cost.[13]

Besides the cost involved, this approach is very time-consuming. More agile competitors can beat the enterprise to market. Since a significant portion of profit from a new product or service comes early in the production cycle, it is important to the enterprise that it not be ceded to competitors.[14]

To combat the problem of long development cycles and to reduce the degree of late engineering change, concurrent engineering was proposed for especially complex design efforts. Concurrent engineering promised to remove the problems in a design cycle by concurrently developing the product design as well as the processes necessary for production, test, and after-market support.

The concept was quite simple and theoretically dealt with the problem. Unfortunately, except for a few isolated cases, concurrent engineering did not fulfill its promise. It fell short for two rather simple reasons. First of all, by its nature it still involved only *engineering.* There was still no drive to include marketing, finance, production operators, testers, and so on. These people bring significant

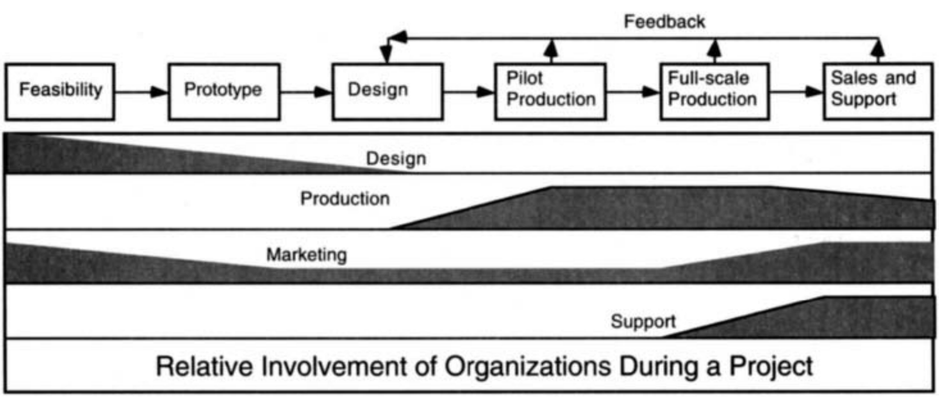


Fig. 72.16 In traditional design, involvement is often partitioned.

insight into issues that affect cost and reliability. The second reason for concurrent engineering's lack of success comes from the nature of organizations. As they currently exist for most companies, functional organizations do not communicate well. Since concurrent engineering did nothing to improve this problem, those outside product design still often had to design their processes in a vacuum, isolated from each other.

Obviously, concurrent engineering, by itself, was not the answer. It would take more to improve the design process.

72.5.8 Cultural/Social Tools—Teams

In the 1980s and before, some leaders started to picture a vision of a radically different organizational structure. One 1990 annual report pictured "a boundaryless company . . . where we knock down the walls that separate us from each other on the inside and our key constituencies on the outside" (Ref. 15, p. 63). Increasingly, business leaders saw teams as a way to solve the design cycle problem and make the enterprise more flexible and agile.

To see how this works, consider the traditional hierarchical organization. Individual elements of this organization are connected through their management chain. How does any department request support of another? Since the powers of budget and personnel evaluation flow from the manager, department staff respond to their manager. Requests for support must be made through the management chain and must often be accompanied with necessary funding. Such funding must be authorized by the giving department's manager and usually involves the two supporting finance organizations, one to prepare the document authorizing funding and one to receive the funding and set up charge-collection systems. A relatively simple request for support can easily involve six people and significant documentation. This is not conducive to a rapid response!

Now let's picture another approach. In this organization, a project team is formed with the responsibility to complete the project. This team may have total responsibility for the new product or service, or it may have responsibility for a subset of the project. The team is given the budget for the project. The team is staffed with representatives of all pertinent functional areas (a multifunctional team). Such a team has the capability to overcome the barriers of traditional organizations.

Teams have been successfully applied on many projects, but the most recent evolution of team applications finally fulfills the promises of concurrent engineering. Referred to as an *integrated product and process development* (IPPD or IPD) team, this approach uses multifunctional teams to develop concurrently the processes and the design of new products and services.

72.5.9 Cultural/Social Tools—The Variability Reduction Process (VRP)

One clear message has emerged from research and observation of various companies' attempts at TQM. Implemented correctly, TQM can be an important strategic weapon for the enterprise. Implemented poorly, it can not only fail to yield promised results, it can be a drag on the enterprise as time and resources are diverted to poorly planned exercises.

The way to avoid an ineffective TQM initiative is to insure that it drives toward goals that can really help the business. A way to achieve such an impact is to use the VRP to focus your TQM efforts. As can be seen in Fig. 72.17, any business has certain key core functions. No matter what the enterprise does, it must

1. Identify customer needs
2. Develop or deploy needed business functions

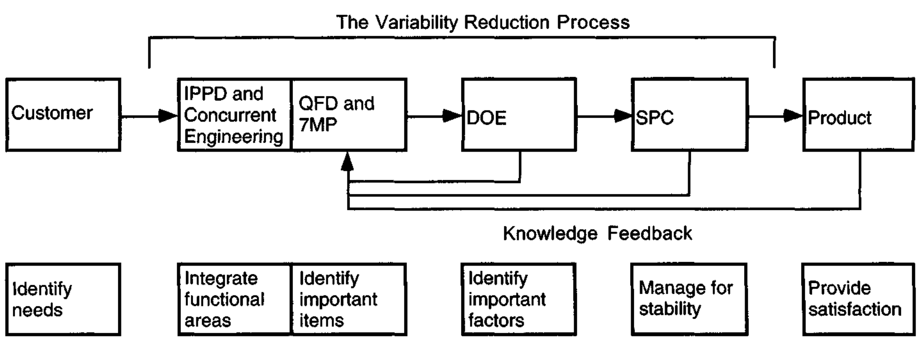


Fig. 72.17 The variability reduction process will guide TQM application.

3. Identify key processes
4. Set key process factors to deliver required performance
5. Manage the processes in a stable manner
6. Meet customer needs

The VRP organizes key TQM tools around the core business functions. These tools may be applied to improve each step. The effect is to engage the whole enterprise in continuous improvement of all processes with a focus on customer needs. Such an approach can significantly transform the enterprise.

72.6 SUMMARY

TQM is a strategic tool for many world-class companies today. It will be a part of the work life for most mechanical engineers and managers. Greater knowledge of the tools and methodologies will be beneficial to your career and to your employees.

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