CHAPTER 3

QUALITY IMPROVEMENT AND COST REDUCTION

3.1 SPORADIC AND CHRONIC QUALITY PROBLEMS

Of the trilogy of quality processes (see Section 1.5., "Managing for Quality"), the process of quality improvement plays a dominant role in reducing costs.

The costs associated with poor quality are due to both *sporadic* and *chronic* quality problems (see Figure 3.1). A sporadic problem is a sudden, adverse change in the status quo, which requires remedy through *restoring* the status quo (e.g., changing a depleted reagent chemical). A chronic problem is a long-standing adverse situation, which requires remedy through *changing* the status quo (e.g., revising an unrealistic specification).

"Continuous improvement" (called Kaizen by the Japanese) has acquired a broad meaning, i.e., enduring efforts to act upon both chronic and sporadic problems and to make refinements to processes. For chronic problems, it means achieving better and better levels of performance each year; for sporadic problems, it means taking corrective action on periodic problems; for process refinements, it means taking such action as reducing variation around a target value.

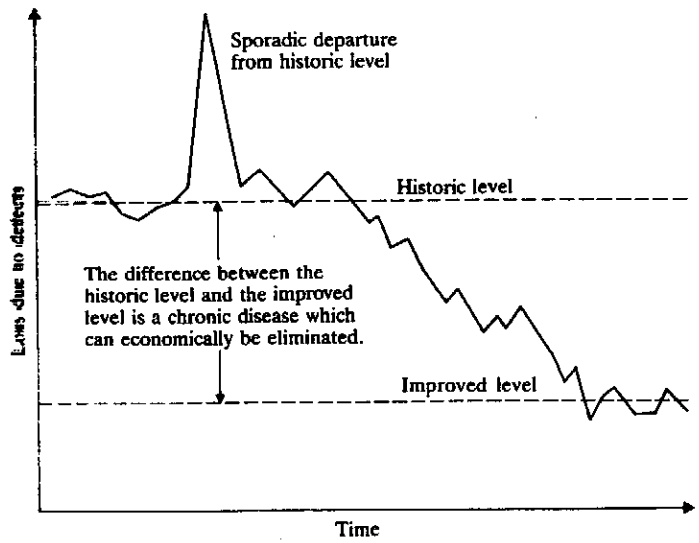

FIGURE 3.1
Sporadic and chronic quality problems.

The distinction between chronic and sporadic problems is important for two reasons:

1. The approach to solving sporadic problems differs from that to solving chronic problems. Sporadic problems are attacked by the control process defined and developed in Chapter 5. Chronic problems use the improvement process discussed in this chapter.
2. Sporadic problems are dramatic (e.g., an irate customer reacting to a shipment of bad parts) and must receive immediate attention. Chronic problems are not dramatic because they occur for a long time (e.g., 2 percent scrap has been typical for the past five years), are often difficult to solve, and are accepted as inevitable. The danger is that the fire fighting on sporadic problems may take continuing priority over efforts to achieve the larger savings that are possible, i.e., on chronic problems.

Addressing chronic quality problems achieves a breakthrough to an improved level of quality (Figure 1.3). This is best achieved by the "project-by-project" approach.

3.2 PROJECT-BY-PROJECT APPROACH

The most effective approach to improvement is "project by project." Here, a project is a chronic, quality-related problem which has been chosen for solution.

The sequence of steps listed in Table 1.5 provides for (1) setting up the project approach and (2) executing the individual projects. Setting up the approach comprises three main steps:

- Proving the need
- Identifying projects
- Organizing project teams

Carrying out each project involves:

- Verifying the project need and mission
- Diagnosing the causes
- Providing a remedy and proving its effectiveness
- Dealing with resistance to change
- Instituting controls to hold the gains

Improvement results on specific projects are limited only by our imagination. We need to question all traditions and assumptions about work activities and also aim for large improvements. Some people call this "reengineering the work" (see Hammer, 1990).

To provide perspective on individual projects, we first present a summarized example. Discussion of the steps in the improvement process then follows.

3.3 EXAMPLE OF A PROJECT

The problem (Betker, 1983) concerns the soldering process used at the GTE Corporation in the manufacture of printed circuit boards (PCBs). A typical PCB has 1700 solder connections. Any defective solder connection can cause testing problems or performance and reliability problems for the customer. We will trace the steps of the improvement sequence for an individual project.

Verify the Project Need and Mission

Over 15 percent of observations exceeded control limits and a large number of solder connections required "touch-up." The project team's mission was to reduce the number of defective solder connections.

Diagnose the Causes

A team of people, not from one department but from several cross-functional departments, was set up to guide the project and do the diagnosis. Figure 3.2 (a "Pareto diagram") depicts the distribution of symptoms by type of solder defect. Data on the defects were analyzed and theories were offered on the causes of the defects. Figure 3.3 is a cause-and-effect diagram summarizing the

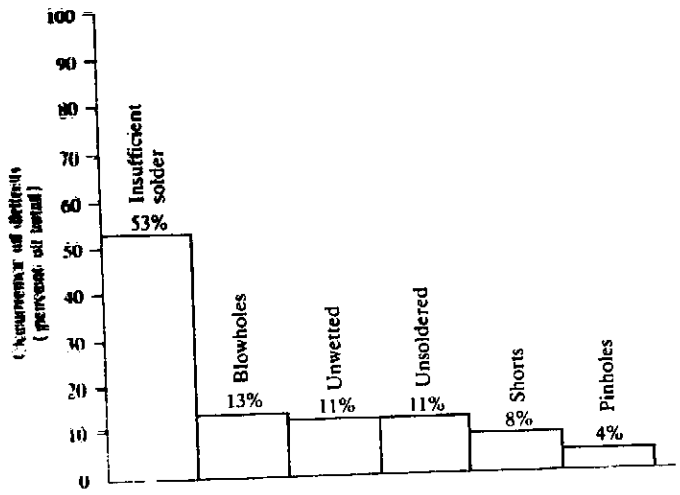

FIGURE 3.2
Solder defect types, Pareto analysis. (*From Betker, 1983.*)

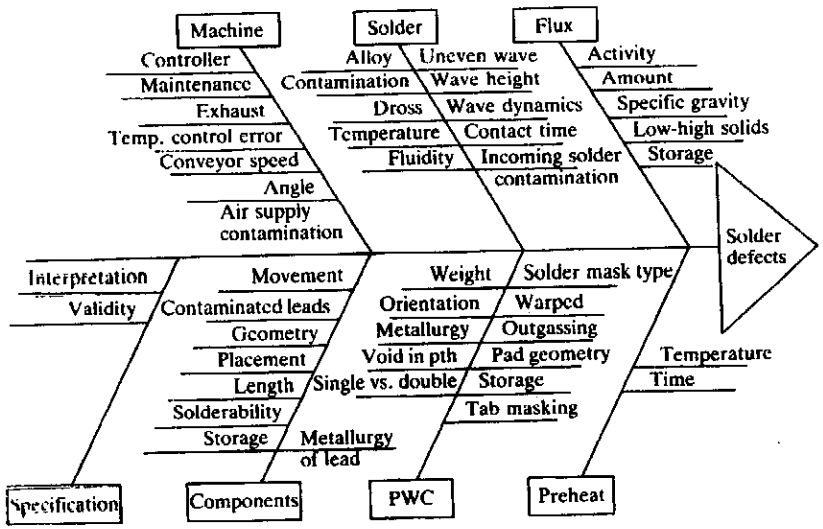

FIGURE 3.3
Ishikawa cause-and-effect diagram. (*From Betker, 1983.*)

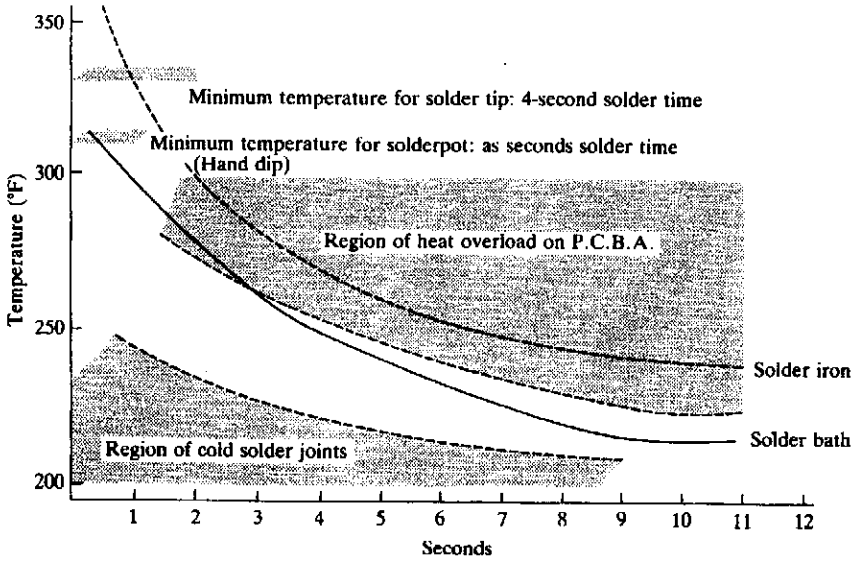

FIGURE 3.4
Temperature/time relationship when flow or dip soldering is applied. (*From Betker, 1983.*)

theories. These theories were grouped into three categories, thereby allowing a checklist to be developed that was used by supervisors and the control inspector to evaluate the theories. After additional data collection and analysis, low solder temperature was found to be the main cause of defects. Figure 3.4 shows a part of the analysis.

Provide a Remedy and Prove Its Effectiveness

Data and further analysis revealed that, for ideal soldering conditions, either the temperature of the solder should be raised or the conveyor speed of the wave soldering machine should be reduced. These were remedies to remove the cause. A trial was conducted using a higher temperature. This resulted in an improvement in solder defects without any adverse effects.

Deal with Resistance to Change

From the start of the project, a manufacturing engineer on the team argued that the cause was outside the control of the machine. The diagnosis explained above convinced him otherwise. But he felt that raising the temperature would result in "reflow of tin under the solder mask, thereby causing solder shorts and peeling of the solder mask." This belief, based on a trial conducted 10

years earlier on other equipment, had been expressed so often that it was no longer questioned. The proof of the remedy step overcame this resistance.

Institute Controls to Hold the Gains

The defect level was reduced by 62 percent and the out-of-control points on statistical control charts were eliminated. To assure that the improved level was maintained, the process was monitored. Not only was the improved level maintained but the elimination of the dominant cause (low temperature) unmasked other causes. Performance has been improved to the point that the hand solder touch-up operation may be eliminated.

This example provides an overview of the entire breakthrough sequence in manufacturing. Chapter 22 illustrates the breakthrough sequence for administrative and support activities. Next we examine the three steps for setting up the project-by-project approach.

3.4 PROVE THE NEED

This step consists of convincing the appropriate level of management that the quality issue is significant enough to require a new approach. Such justification starts with a companywide improvement effort but also applies to individual projects.

Chronic problems often require substantial time and resources for investigation, and thus the need must be justified. If solutions were easy, the problems would not be chronic.

To gain management approval for a new approach to quality:

1. Collect factual information to show the size of the quality problem. Experience shows that studies on the costs of poor quality and on competitive standing in the marketplace are convincing methods (see Chapter 2).
2. Show the benefits possible from an improvement program and use this to justify the resources requested for the program. This might take the form of percentage return on investment, time required to pay back the investment through savings, or other measures. Even when there is agreement on the importance of a problem, it is still helpful to quantify the size of the quality loss and the potential savings, because they can justify a sufficient investment to solve the problem.

The Several Languages of Management

To establish proof of the need, different "languages" may be required for different levels of management. For upper management, the language of money works best; for lower levels, other languages are effective. Table 3.1 shows examples of statements in money and other languages.

TABLE 3.1
Languages of management

Money (annual cost of poor quality)
24% of sales revenue
15% of manufacturing cost
13 cents per share of common stock
$7.5 million per year for scrap and rework compared to a profit of $1.5 million per year
$176 million per year
40% of the operating cost of a department
Other languages
The equivalent of one plant in the company making 100% defective work all year
32% of engineering resources spent in finding and correcting design weaknesses
25% of manufacturing capacity devoted to correcting quality problems
13% of sales orders canceled
70% of inventory carried attributed to poor quality levels
25% of manufacturing personnel assigned to correcting quality problems

Use of a Bellwether Project

An even more effective way to achieve a breakthrough in the attitude of management is to couple the study on the cost of poor quality with a case example of a successful quality improvement project within the company. This is illustrated in the approach taken by the ABC electronics company.

The estimated cost of poor quality was $200 million per year and a notorious quality problem was scrap for a certain major electronic component. This scrap ran to about $9 million per year. The principal defect type was defect *X*, and it was costing about $3 million per year ("proof of the need" for eliminating defect *X*).

The company took on a project to reduce the incidence of defect *X*. The project was a stunning success. The cost of defect *X* was cut from $3 million to $1 million—an annual profit improvement of $2 million. An investment of about $250,000 was needed.

Then followed an exciting extrapolation and contrast. It was estimated that extension of the improvement to the entire $200 million cost of poor quality could cut the total in half—thus creating a profit improvement of $100 million annually.

The defect *X* project proved to the ABC company managers that they could get a big return on investment by improving quality. This in-house project was more convincing to results-oriented managers than any number of lectures, books, or success stories about other companies.

But proof of the need is also important for *each* project for two reasons: (1) to confirm that the project is significant enough to justify spending the time to do diagnosis and (2) to show the potential benefits. For example, the

monthly closing of the books in an accounting function incurred a 2.5 percent error rate. This translated into about 5000 miscodes per day during the closing period. Those miscodes resulted in large failure costs, high overtime, and low morale. Such information gave the impetus for an improvement study that resulted in an 80 percent reduction in miscodes, elimination of most of the overtime, and a great improvement in morale (*Fortune*, 1985).

3.5 IDENTIFY PROJECTS

Breakthrough is achieved project by project. Project identification consists of nominating, screening, and selecting projects.

Nomination for Projects

Nominations come from several sources:

- Analysis of data on the cost of poor quality, quality standing in the marketplace, or other forms of assessment (see Chapter 2)
- Analysis of other field intelligence, e.g., inputs from Sales, Customer Service, and other personnel
- Goal-setting processes, e.g., the annual budget, management by objectives
- All levels of management and the work force
- Developments arising from the impact of product quality on society, e.g., government regulation, growth of product liability lawsuits

A data analysis tool for generating project nominations is the Pareto principle.

The Pareto Principle

As applied to the cost of poor quality, the Pareto principle states that a few contributors to the cost are responsible for the bulk of the cost. These vital few contributors need to be identified so that quality improvement resources can be concentrated in those areas.

A study of quality-related costs at a paper mill showed a total of $9.07 million (Table 3.2*a*). The category called "broke" (paper mill jargon for paper so defective that it is returned to the beater for reprocessing) amounts to $5.56 million, or 61 percent of the quality costs. Clearly, there will be no major reduction in these costs unless there is a successful attack on the broke—which is where the loss of money is concentrated.

In that paper mill, 53 types of paper are made. When the broke is allocated among the various types of paper, the Pareto principle is again in evidence (Table 3.2*b*). Six of the product types account for $4.48 million, which is 80 percent of the $5.56 million. There will be no major improvement

TABLE 3.2*a*
Pareto analysis by accounts—quality losses in a paper mill

Accounting category	Annual quality loss,* $ thousands	Total quality loss, %	
		This category	Cumulative
"Broke"	5560	61	61
Customer claim	1220	14	75
Odd lot	780	9	84
High material cost	670	7	91
Downtime	370	4	95
Excess inspection	280	3	98
High testing cost	190	2	100
Total	9070		

* Adjusted for estimated inflation since time of original study.

TABLE 3.2*b*
Pareto analysis by products—"broke" losses in a paper mill

Product type	Annual "broke" loss,* $ thousands	"Broke" loss, %	"Broke" loss, cumulative %
A	1320	24	24
B	960	17	41
C	720	13	54
D	680	12	66
E	470	8	74
F	330 (4480)	6	80
47 other types	1080	20	100
Total 53 types	5560	100	

* Adjusted for estimated inflation since time of original study.

TABLE 3.2*c*
Matrix of quality costs*

Type	Trim, $ thousands	Visual defects, † $ thousands	Caliper, $ thousands	Tear, $ thousands	Porosity, $ thousands	All other causes, $ thousands	Total, $ thousands
A	270	94	None‡	162	430	364	1320
B	120	33	None‡	612	58	137	960
C	95	78	380	31	74	62	720
D	82	103	None‡	90	297	108	680
E	54	108	None‡	246	None‡	62	470
F	51	49	39	16	33	142	330
Total	672	465	419	1157	892	875	4480

* Adjusted for estimated inflation since time of original study.

† Slime spots, holes, wrinkles, etc.

‡ Not a specified requirement for this type.

in broke unless there is a successful attack on these six types of paper. Studying 12 percent (6 types out of 53) of the problem results in attacking 80 percent of the broke.

Finally, it is helpful to look at what kinds of defects are being encountered in these six types of paper, and how much the associated costs for broke are. The matrix of Table 3.2*c* shows this analysis. There are numerous defect types, but five dominate. In addition, the cost figures in the table also follow the Pareto principle. The largest number is $612,000 for tear on paper type *B*, then comes $430,000 for porosity on *A*, and so on. Such analysis would be helpful in nominating projects for cost reduction.

Establishing Priorities for Projects

Typically, project nominations are reviewed by middle management and recommendations are then made to upper management for final approval.

The review varies from an analysis of the project scope and potential benefit to a formal examination of several factors to help set priorities. For example, Berry (1988) explains how the Colonial Penn Insurance Company screens potential projects by asking six questions: Can we impact? Can we analyze? Are data available? Are they measurable? What areas are affected? What is the level of control?

Hartman (1983) describes an approach at AT&T that makes use of a "Pareto Priority Index" (PPI) to evaluate each project. The index is:

$$\text{PPI} = \frac{\text{Savings} \times \text{probability of success}}{\text{Cost} \times \text{time to completion (years)}}$$

Table 3.3 shows the application of this index to five potential projects. High PPI values suggest high priority. Note how the ranking of projects *A* and *C* is affected when the criterion is changed from cost savings alone to the index covering the four factors.

The result of the review by middle management is a recommended list of projects. Typically, one responsibility of an upper management quality council is reviewing the recommendations or creating the organizational machinery for review and final approval.

TABLE 3.3
Ranking by use of Pareto Priority Index (PPI)

Project	Savings, $ thousands	Probability	Cost, $ thousands	Time, years	PPI
A	100	0.7	10.0	2.0	3.5
B	50	0.7	2.0	1.0	17.5
C	30	0.8	1.6	0.25	60.0
D	10	0.9	0.5	0.50	36.0
E	1.5	0.6	1.0	0.10	9.0

Selection of Initial Projects

"The first project should be a winner." A successful project is a form of evidence to the project team members that the improvement process does lead to useful results. Ideally:

- The project should deal with a chronic problem—one which has been awaiting solution for a long time.
- The project should be feasible, i.e., have a good likelihood of being brought to a successful conclusion within about six months.
- The project should be significant. The end results should be sufficiently useful to merit attention and recognition.
- The results should be measurable in money as well as in technological terms.
- The project should serve as a learning experience for the process of problem solving.

Problem and Mission Statement

A problem statement identifies a visible deficiency in a planned outcome, e.g., "During the past year, 7 percent of invoices sent to customers included errors." A problem statement should never imply a cause or a solution or affix blame.

A mission statement is based upon the problem statement but provides direction to the project team. If possible, a goal or other measure of project completion and a target date should be defined. For example, the team is asked to reduce the error rate in invoices to 2 percent or less within the next 6 months.

3.6 ORGANIZE PROJECT TEAMS

A project team usually consists of about six to eight persons who are drawn from multiple departments and assigned to address the selected problem. Their job is to bring the project to a successful conclusion as defined in the mission statement for the project.

The team meets periodically and members serve part time in addition to performing their regular functional responsibilities. When the project is finished, the team disbands.

The project team consists of a leader, a secretary, and other team members. (Consulting specialists from disciplines such as accounting, software, metallurgy, etc., are invited to meetings when needed.)

PROJECT TEAM LEADER. The project team leader steers the team in its responsibility of carrying out the project. Successful leadership requires knowledge of the project area and skills in getting team members from several functional areas to work as a team. It is often useful for the team leader to come from the organizational unit most impacted by the problem.

PROJECT SECRETARY. Each team requires a project secretary to handle documentation: agendas, minutes, reports, etc. The secretary should be a member of the project team.

PROJECT TEAM MEMBERS. Team membership draws upon all of the skills and knowledge necessary for the project. For chronic problems, the teams are usually cross-functional and consist of middle management, professional, and work force personnel. Surprisingly, some projects are relatively easy and can be handled with a minimum of skills and knowledge. (Such projects are often the result of a previous lack of a project approach.) Other projects are complex and require more depth in team membership, perhaps even including consulting specialists from within the company.

Supplementing the formal team membership is a "facilitator." Many companies have adopted the concept of using a facilitator to help project teams carry out their first project. Although not a member of the team, the facilitator can play an important role. The role of the facilitator consists of any or all of the following:

- Explaining the company's approach to quality improvement and how it differs from prior efforts at quality improvement
- Providing assistance in team building
- Assisting in the training of project teams
- Assisting the project team leader to solve human relations problems among team members
- Helping the team avoid a poor choice of project
- Reporting progress on projects to management
- Revitalizing a stalled project

PROJECT TEAMS: INTRADEPARTMENTAL AND INTERDEPARTMENTAL. The vital few chronic problems usually cut across department lines and require cross-functional "project teams." Other chronic problems are centered within one department. Some of these problems can be solved by individuals, but many call for departmental teams called "Quality Circles" or "employee involvement groups," which we will discuss in Chapter 7.

While both types of teams are essential, there are important differences between the two (see Table 3.4).

A companywide effort on improvement involves many teams (and other individual activities). This, in turn, requires setting up the machinery to select problems and then form, train, monitor and provide time and recognition for

TABLE 3.4
Comparison: quality circles and project teams

Feature	Quality circles	Project teams
Scope of project	Within a single department	Multidepartmental
Size of project	One of the useful many	One of the vital few
Members come from	A single department	Multiple departments
Basis of membership	Voluntary	Mandatory
Composition of membership	Work force	Mostly middle management and specialists
Continuity	Circle remains intact, project after project	Team is ad hoc, disbands after project is completed

these teams. A companywide Quality Council usually has this responsibility, as will be discussed in Chapter 7.

3.7 EXPERIENCES WITH THE PROJECT-BY-PROJECT APPROACH

Experiences in both manufacturing and service industries have led to encouraging conclusions:

- Large cost reductions and improved quality to customers have been achieved. For each dollar invested in improvement activity, the return is between 5 and 10 dollars.
- Investment required for improvement has been modest and *not* capital intensive. Most of the investment is in the time of people doing diagnosis for the projects.
- Most projects can be completed in 6 months if the scope in the mission statement is carefully defined.
- The key chronic quality-related problems cut across departments and thereby require cross-functional project teams.

An increasing number of companies have reported the completion of over a thousand projects during a period of about 4 years. Today's competitive business conditions dictate such a revolutionary rate of improvement to replace the evolutionary rate of the past.

3.8 BREAKTHROUGH SEQUENCE FOR AN INDIVIDUAL PROJECT

Individual projects are selected, a problem and mission statement is prepared, and a project team is organized for each project. The team should then follow

a sequence of steps to solve the problem. The following sequence has a good track record.

3.9 VERIFY THE PROJECT NEED AND MISSION

Presumably, a project has been selected because it is "important." It is useful, however, to verify the size of the problem *in numbers*. This serves two purposes: (1) assure that the time to be spent by the project team is justified and (2) help to overcome resistance to accepting and implementing a remedy. Verifying the need for an individual project makes use of the same type of information discussed above under "Prove the Need." It is also essential that the *scope* of the project be reviewed after the team has met once or twice, to be sure that the mission assigned to the team can be accomplished within, say, about 6 months. Otherwise, the project should be divided into several projects. Failure is likely if a project stretches out like a freight train.

3.10 DIAGNOSE THE CAUSES

Diagnosis is the process of studying the symptoms of a problem and determining their cause(s). The beginning of diagnosis is collecting data on the symptoms; the end is agreement on the causes.

Many managers harbor deep-seated beliefs that most defects are caused during manufacture and specifically are due to worker errors, i.e., that defects are mainly worker-controllable. The facts seldom bear this out, but the belief persists. To deal with such deep-seated beliefs, it can be useful to conduct studies to separate defects into broad categories of responsibility. Such studies include:

1. A study to determine the origin of the defects in the design, manufacture, etc. Such a study to determine the distribution of causes over functional areas often has some surprising results. In a classic study, Greenidge (1953) examined 850 failures of electronic products supplied by a number of companies. The results showed that 43 percent of the failures were caused by the product design, 30 percent by field operation conditions, 20 percent by manufacturing, and the remaining 7 percent by miscellaneous causes. For products of moderately high technology, it is not unusual for about 40 percent of field problems to be traceable to the product design.
2. A study to determine whether defects are primarily management-controllable or worker-controllable ("management" here includes not only people in supervisory positions but also others who influence quality, e.g., design engineers, process engineers, buyers, etc.). In general, defects are more than 80 percent management-controllable and less than 20 percent worker-controllable. Some authors use the term "system-controllable" for "management-controllable."

Such broad studies provide important guidance for improvement.

Some relevant definitions are:

A *defect* is any nonfulfillment of intended usage requirements, e.g., oversize, low mean time between failures, illegible invoice. A defect can also go by other names, e.g., error, discrepancy, nonconformance.

A *symptom* is an observable phenomenon arising from and accompanying a defect. Sometimes, but not always, the same word is used both as a defect description and as a symptom description, e.g., "open circuit." More usually, a defect will have multiple symptoms; e.g., "insufficient torque" may include the symptoms of vibration, overheating, erratic function, etc.

A *theory* is an unproved assertion as to reasons for the existence of defects and symptoms. Usually, several theories are advanced to explain the presence of the observed phenomena.

A *cause* is a proven reason for the existence of the defect. Often, there are multiple causes, in which case they follow the Pareto principle, i.e., the vital few causes will dominate all the rest.

A *remedy* is a change that can successfully eliminate or neutralize a cause of defects.

Two journeys are required for quality improvement: the diagnostic journey from symptom to cause, and the remedial journey from cause to remedy. This distinction is critical. To illustrate, three supervisors were faced with a problem of burrs on screws at the final assembly of kitchen stoves. In their haste to act, they skipped the diagnostic journey and concluded that better screws were needed (a remedy). Fortunately, a diagnostician interceded. He pointed out that three separate assembly lines were feeding product into one inspection station, and he suggested that the data be segregated by assembly line. The data revealed that the burrs occurred only on line 3. Further diagnosis based on data led to agreement that the true cause was an improperly trained assembler. Then the remedy came easily.

The diagnostic journey consists of:

1. Study of the symptoms surrounding the defects to serve as a basis for theorizing about causes
2. Theorizing on the causes of these symptoms
3. Data collection and analysis to test the theories and thereby determine the causes

Many analysis techniques are available to assist in these three steps. Some are illustrated in the following pages. A compilation with examples is provided in QCH4, Section 22. This compilation includes the "Magnificent Seven" tools: control chart, checksheet, histogram, Pareto diagram, cause-and-effect diagram, scatterplot, and flowchart. Additional tools continually emerge.

Evidence of defects and errors comes in two forms:

1. Words used in written documentation or oral comments describing the problem
2. "Autopsies" conducted to measure and examine the defects

Description of Symptoms

Understanding of symptoms is often hindered because some key word or phrase has multiple meanings.

In one example, a Pareto analysis of inspection data in a wire mill indicated a high percentage of defects due to "contamination." Various remedies were tried to prevent the contamination. All were unsuccessful. In desperation, the investigators spoke with the inspectors to learn more about the contamination. The inspectors explained that there were 12 defect categories on the inspection form. If the observed defect did not fit any of the categories, they would report the defect as "contamination."

Imprecise wording also occurs due to use of generic terminology. For example, a software problem is described in a discrepancy report as a "coding error." Such a description is useless for analysis because there are many types of coding errors, e.g., undefined variables, violation of language rules, and violation of programming standards.

A way out of such semantic tangles is to think through the meanings of the words used, reach an agreement, and record the agreement in the form of a glossary. Once published, the glossary simplifies the subsequent analysis.

Quantification of Symptoms

The frequency and intensity of symptoms are of great significance in pointing to directions for analysis. The Pareto principle, when applied to records of past performance, can help to quantify the symptom pattern. Figure 3.5 displays a Pareto diagram for deficiencies in the handling of classified information at the Honeywell Corporation. Seven categories of symptoms were identified, e.g., "container improperly secured" and "unattended material." The Pareto principle applies to several levels of diagnosis: finding the vital few defects, finding the vital few symptoms of a defect, and finding the vital few causes of one symptom.

Formulation of Theories

The process consists of three steps: generation of theories, arrangement of theories, and choice of theories to be tested.

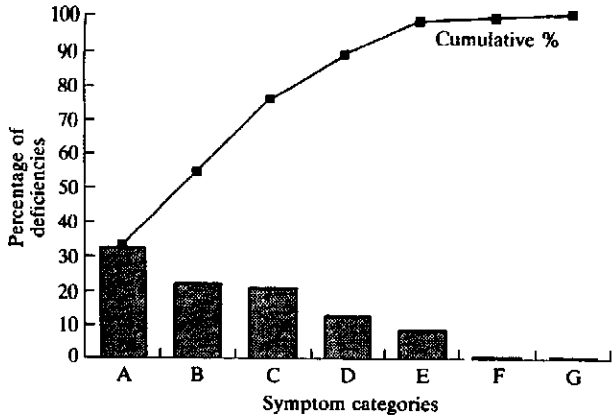

FIGURE 3.5
Pareto analysis of security violations. (*From Parvey, 1990.*)

GENERATION OF THEORIES. The best sources of theories are the line managers, the technologists, the line supervisors, and the work force. A systematic way to generate theories is the brainstorming technique. Persons who are potential contributors are assembled for the purpose of generating theories. Creative thinking is encouraged by asking each person, in turn, to propose a theory. No criticism or discussion of ideas is allowed, and all ideas are recorded. The end result is a list of theories which, after the brainstorming session is completed, are critically reviewed.

A useful supplement to the brainstorming technique is "storyboarding." Each theory proposed is recorded on an index card. The cards are arranged on a board to form a visual display of the theories. Storyboarding provides a visual system for organizing theories and planning subsequent evaluation of these theories.

ARRANGEMENT OF THEORIES. Normally, the list of theories should be extensive, 20 or more. As the list grows in size, it is essential to create an orderly arrangement. Such order helps us to understand the interrelationships among theories and to plan for testing of the theories. Table 3.5 shows a tabular arrangement of theories contributing to low yield of a process making fine powder chemicals. The theories consist of major variables and contributing subvariables. A second method, which is highly effective, is a graphical arrangement called the Ishikawa cause-and-effect (or "fishbone") diagram. Figure 3.6 shows such a diagram, which presents the same information as is listed in Table 3.5. QCH4, pages 22.39–22.40, discusses other methods of arranging theories.

CHOOSING THEORIES TO BE TESTED. After the theories are arranged in an orderly fashion, priorities must be established for testing the theories. In

TABLE 3.5
Orderly arrangement of theories

- Raw material
  - Shortage of weight
  - Method of discharge
- Catalyzer
  - Types
  - Quantity
  - Quality
- Reaction
  - Solution and concentration
  - B solution temperature
  - Solution and pouring speed
  - pH
  - Stirrer, rpm
  - Time
- Crystallization
  - Temperature
  - Time
  - Concentration
  - Mother crystal
    - Weight
    - Size
- Moisture content
  - Charging speed of wet powder
  - Dryer, rpm
  - Temperature
    - Stream pressure
    - Steam flow
- Overweight of package
  - Type of balance
  - Accuracy of balance
  - Maintenance of balance
  - Method of weighing
  - Operator
- Transportation
  - Road
  - Cover
  - Spill
  - Container

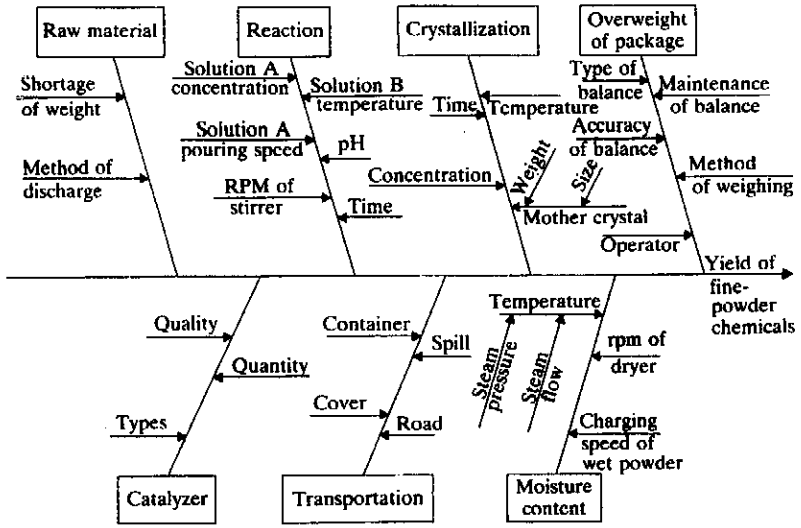

FIGURE 3.6
Ishikawa cause-and-effect diagram.

practice, the improvement team reaches a consensus on the "most likely" theory for testing. Whether to test just one theory at a time, one group of interrelated theories at a time, or all theories simultaneously requires a judgment based on the experience and creativity of the team.

We proceed next to the test of theories—first, management-controllable, then worker-controllable.

Test of Theories of Management-Controllable Problems

Numerous diagnostic methods have been created to test theories. Some are illustrated below; others abound in the literature.

PRODUCT AND PROCESS DISSECTION. Some products are produced by a "procession" type of process, i.e., a series of sequential operations. At the end of the series, the product is found to be defective, but it is not known which operation did the damage. In some of these cases, it is feasible to dissect the process, i.e., make measurements at intermediate steps in the process to discover at which step the defect appears. Such a discovery can drastically reduce the subsequent effort in testing theories.

FLOW DIAGRAM. Dissection of a process is aided by constructing a flow diagram (recent jargon is "process map") showing the various steps in the process. Engle and Ball (1986) explain the role of a flow diagram in reducing the time required for handling special customer orders. Thus we have a process—a cycle of steps to handle special customer orders—and we need to reduce the process cycle time. A quality improvement team discovered that no one was able to describe the special order process. To understand the process they were trying to improve, the team created a flow diagram. Examples of several types of diagrams for understanding a process are given in Section 16.2, "Initial Planning for Quality."

PROCESS CAPABILITY ANALYSIS. One of the theories most widely encountered is "The process can't hold the tolerances." To test this theory, measurements from the process must be taken and analyzed to determine the amount of variability inherent in the process. This variability is then compared to the specification limits. Those steps are performed in a "process capability" study (see Section 17.8, "Process Capability").

STREAM-TO-STREAM ANALYSIS. In order to meet production volume requirements, several sources of production ("streams") are often necessary. Streams take the form of different machines, operators, shifts, suppliers, etc. Although the streams may seem to be identical, the resulting products may not be. Stream-to-stream analysis consists of recording and examining data separately for each stream.

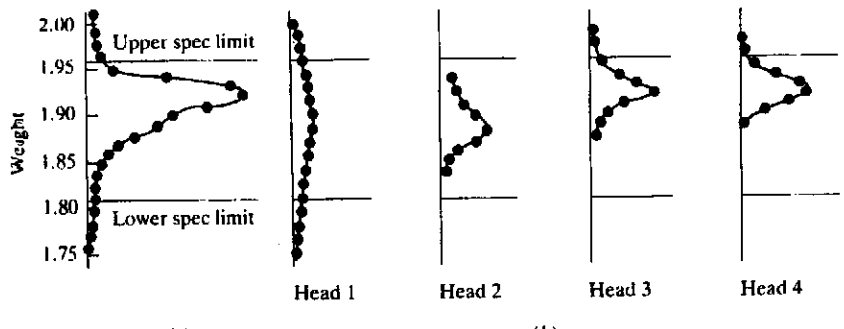

FIGURE 3.7
Distribution of glass bead weights: (*a*) sum of four heads, (*b*) weight distribution on each of the four heads. (*From QCH4*, p. 22.42.)

An example (Payne, 1984) comes from a glass tube cutting machine. Glass tubing was cut into small glass rings. The weight of the rings was the critical element in determining the properties of the finished glass product. A sample of data (Figure 3.7*a*) apparently confirmed a theory that the machine was not functioning correctly. However, the machine contained four heads. Data collected separately from each head (stream) revealed that there was nothing wrong with heads 2, 3, 4—except for a need to recenter their position (Figure 3.7*b*). There was, however, something wrong with head 1. Ultimately, the remedy was proper maintenance of the machine rather than a redesign of the machine, as had originally been contemplated based on Figure 3.7*a*.

TIME-TO-TIME ANALYSIS. Time-to-time analyses include: (1) a simple plot of data on a time scale; (2) analysis of the time between abnormalities or problems; (3) analysis of the rate of change, or "drift," of a characteristic; and (4) the use of cumulative data techniques with respect to time. Examples are given below.

In one example, field failures of oil coolers were assumed to be due to manufacturing. A parade of remedies (skipping the journey from symptom to cause) resulted in zero improvement. An engineer decided to plot the frequency of failures by month of the year, and this led to an important discovery. Of 70 failures over a 9-month period, 44 occurred during January, February, and March. These facts shifted the search to other causes such as winter climatic conditions. Subsequent diagnosis revealed the cause to be in design rather than manufacturing.

In analyzing time-to-time variations, the length of time between abnormalities can be a major clue to the cause. In a textile carding operation, there was a cyclic rise and fall in yarn weights, the cycle being about 12 minutes in

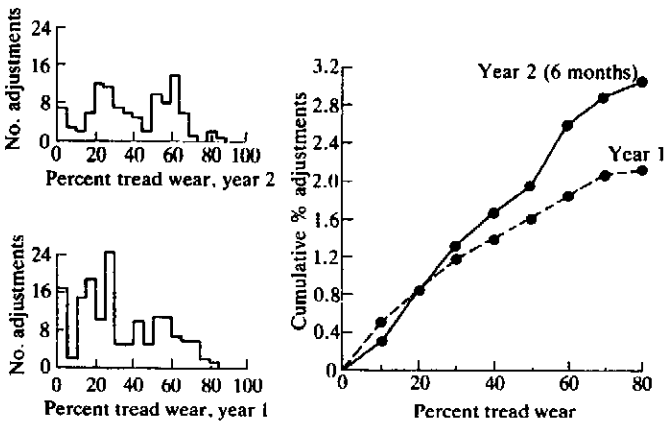

FIGURE 3.8
Comparison of histograms and cumulative plots. (*From QCH4, p. 22.44.*)

length. The reaction of the production superintendent was immediate: "The only thing we do every 12 minutes or so is to stuff that feed box."

Within many streams, there is a time-to-time "drift"; e.g., the processing solution gradually becomes more dilute, the tools gradually wear, the worker becomes fatigued. Such drifts can often be quantified to determine the magnitude of the effect.

Cumulative data plots can help to discover differences that are hidden when the data are in noncumulative form. Figure 3.8 compares histograms (noncumulative) and cumulative plots for data from 2 separate years. A difference in adjustments for year 1 versus year 2 is apparent from the cumulative plot but is hidden in the histogram.

Control charts are a powerful diagnostic tool. Data are plotted chronologically, and the chart then shows whether the variability from sample to sample is due to chance or assignable causes of variation. Detection of assignable causes of variation can be the link to discovering the cause of a problem. Chapter 17, "Statistical Process Control," explains the concept.

ANALYSIS OF PIECE-PART VARIATION. Some products exhibit several types of variation, e.g., piece-to-piece, within-piece, and time-to-time. The multivari chart is a clever tool for analyzing such variation. In this chart, a vertical line depicts the range of variation within a single piece of product. Figure 3.9 depicts three different examples of the relationship of product variation to tolerance limits. The left-hand case is one in which the within-piece variation alone is too great in relation to the tolerance. Hence, no solution is possible unless within-piece variation is reduced. The middle example is a case in which within-piece variation is comfortable, occupying

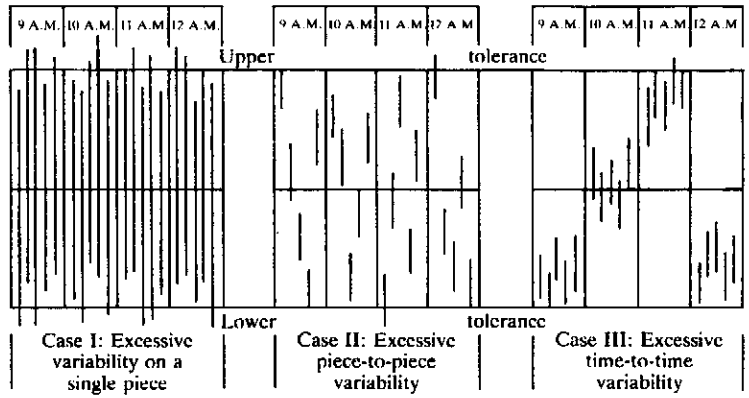

FIGURE 3.9
Multivari chart.

only about 20 percent of the tolerance. The problem, then, is piece-to-piece variation. In the right-hand example, the problem is excess time-to-time variability.

DEFECT-CONCENTRATION ANALYSIS. A different form of piece-to-piece variation is the defect-concentration study used for attribute types of defects. The purpose is to discover whether defects are located in the same physical area. The technique has long been used by shop personnel when they observe that all pieces are defective and in precisely the same way. However, when the defects are intermittent or become evident only in later departments, the analysis can be beyond the unaided memory of the shop personnel.

For example, a problem of pitted castings was analyzed by dividing the castings into 12 zones and tallying up the number of pits in each zone over many units of product. The concentration at the gates (through which the metal flows) became evident, as did areas which were free of pits (Figure 3.10).

ASSOCIATION SEARCHES. Sometimes diagnosis can be advanced by analyzing data relating symptoms of the problem to some theory of causation, pinpointing process, tools, workers, or design. Possible relationships can be examined using various statistical tools such as correlation and matrixes.

Correlation. In this approach, data are plotted that relate the incidence of symptoms of the problem to values of a potential causal variable.

In one case, the symptom was yarn breakage on weaving machines. One theory was "handling damages to the board bobbin" (the spinning mill supplied the yarn reeled onto a board bobbin). A plot of the amount of

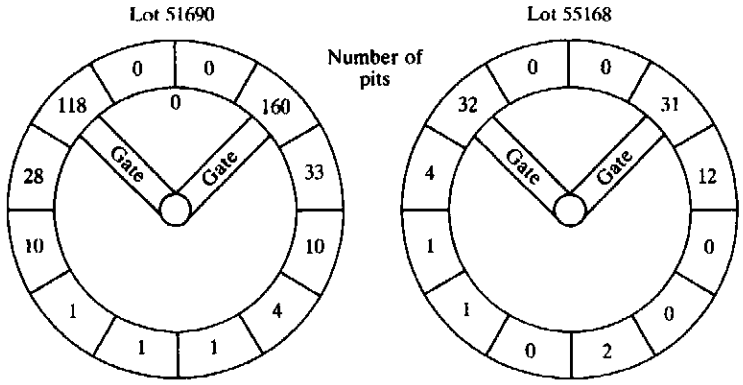

FIGURE 3.10
Concentration of pits in cast rings.

damage versus the number of yarn breakages clearly revealed a relationship between reels with heavy damage and subsequent yarn breakage. Further investigation showed that the corrugated paperboard plates used to protect the bobbins were inadequate. An investment of a few hundred dollars yielded a savings of $10,000 per year, an amount heretofore lost because of yarn breakages (Bergstrom, 1985).

Matrix. In this approach, past or current data are collected on two or more variables of a problem and summarized in a table to see if any pattern exists. In a study involving 23 types of torque tubes, the symptom was dynamic unbalance. One theory was that a swaging operation was a dominant cause. Table 3.6 tabulates the percentage of defective pieces (dynamic unbalance)

TABLE 3.6
Test of theories by ranking

Type	Defective, %	Swaged (marked ×)	Type	Defective, %	Swaged (marked ×)
A	52.3	×	M	19.2	×
B	36.7	×	N	18.0	×
C	30.8	×	O	17.3	
D	29.9	×	P	16.9	×
E	25.3	×	Q	15.8	
F	23.3	×	R	15.3	
G	23.1	×	S	14.9	
H	22.5		T	14.7	
I	21.8	×	U	14.2	
J	21.7	×	V	13.5	
K	20.7	×	W	12.3	
L	20.3				

and also shows if swaging was part of the process. The result was dramatic—the worst seven types of tubes were all swaged; the best seven were all unswaged. This partially confirmed that swaging was a dominant cause. Later analysis revealed an inadequate specification on an important coaxial dimension.

Later in this chapter, the matrix technique for analyzing problems in insurance contracts is illustrated.

TEST OF THEORIES BY COLLECTION OF NEW DATA. In some cases, discovery of causes requires careful examination of additional stages in the process. This "cutting of new windows" can take several forms:

1. *Measurement at intermediate stages of a single operation.* An example concerned a defect known as "voids" in welded joints of pressure vessels. Initial diagnosis established six sources of variation: operator, time-to-time, joint-to-joint, layer-to-layer, within layers, and within one welding "bead." Available past data permitted analysis of the first two sources as possible causes of voids. The remaining three could not be analyzed since the critical X-ray test was performed only when a joint was completely finished. The answer was to "cut a new window" by making an X ray after each of the several beads needed to make a joint. The data established that the main variable was within-bead variation and that the problem was concentrated at the start of the bead.

   An example from a human resources process concerns the time required for hiring new engineers. Measurements taken at six steps in the hiring process formed the basis for a diagnosis of excessive time taken to hire engineers.
2. *Measurement following noncontrolled operations.* Here, diagnosis includes the collection of additional information at individual steps in a process. Marquez (1985) describes the diagnosis of excessive shutdown time for removing a hot mold from a molding machine. The process of shutdown was divided into 11 steps, and measurements were taken to estimate the time required for each step. Two of the 11 steps accounted for 62 percent of the shutdown time. This Pareto effect was important in further diagnosis.
3. *Measurement of additional or related properties of the product or process.* Diagnosis sometimes requires measurements of characteristics other than those for which the specification is not being met. In the manufacture of phonograph records, the symptom was a high percentage of records with surface defects. Automatic timers controlled the pressing cycle. Diagnosis revealed that the times for various steps should not be fixed but should be determined based on additional measurements taken periodically. The remedy was to monitor pressure, temperature, viscosity, and other factors. An on-line computer evaluates these data for each disk and decides on the

optimum molding conditions. Only then, and no sooner, does the press create the product.

4. *Study of worker methods.* In some situations, there are consistent differences in the defect levels coming from various workers. Month after month, some workers produce more "good" product than others. In such situations, there must be a cause for this consistent difference in observed performance. Diagnosis of problems related to human performance is discussed later in this section.

TEST OF THEORIES THROUGH EXPERIMENTS. Experiments in the laboratory or outside world may be necessary to determine and analyze the dominant causes of a quality problem. Four types of diagnostic experiments are summarized in Table 3.7.

Experiments for evaluating one or two suspected variables ("factors") are sometimes called "rifle shot experiments." The purpose is to test a theory that a suspected variable is a major cause of a problem.

In the exploratory experiment, the dominant variables are not known but must be pursued by a formal experiment. This is called an unbridled experiment.

A well-organized exploratory experiment has a high probability of identifying the dominant causes of variability. However, there is a risk of overloading the experimental plan with too much detail. A check on overextension of the experiment is to require that the analyst prepare a written plan for review. This written plan must define:

1. The characteristics of material, process, environment, and product to be observed

TABLE 3.7
Types of diagnostic experiments

Type of experiment	Purpose and approach
Evaluating suspected dominant variables	Evaluate changes in values of a variable by dividing a lot into several parts and processing each portion at some different value, e.g., temperature.
Exploratory experiments to determine dominant variables	Statistically plan an experiment in which a number of characteristics are carefully varied in a manner to yield data for quantifying each dominant variable and the interactions among variables.
Production experiments (evolutionary operation)	Make small changes in selected variables of a process and evaluate the effect to find the optimum combination of variables.
Simulation	Use the computer to study the variability of several dependent variables which interact to yield a final result.

2. The control of these characteristics during the experiment; a characteristic may be:
   (*a*) Allowed to vary as it will and measured as is
   (*b*) Held at a standard value
   (*c*) Deliberately randomized
   (*d*) Deliberately varied, in several classes or treatments
3. The means of measurement to be used (if different from standard practice)

If the plan shows that the experiment may be overloaded, a "dry run" in the form of a small-scale experiment is in order. A review of the dry-run experiment can then help decide the final plan.

Production experiments. Experimentation is often regarded as an activity that can be performed only under laboratory conditions. To achieve maximum performance from some manufacturing processes, however, the effect of key process variables on process yield or product properties must be demonstrated under shop conditions. Laboratory experimentation to evaluate these variables does not always yield conclusions that are completely applicable to shop conditions. When justified, a "pilot plant" may be set up to evaluate process variables. However, the final determination of the effect of process variables must often be done during the regular production run by informally observing results and making changes if these are deemed necessary. Thus, informal experimentation *does* take place on the manufacturing floor.

To systematize informal experimentation and provide a methodical approach for process improvement, G.E.P. Box developed a technique known as "evolutionary operations" (EVOP). EVOP is based on the concept that every manufactured lot has information to contribute about the effects of process variables on a quality characteristic. Although such variables could be analyzed by an experimental design, EVOP introduces *small* changes into these variables according to a planned pattern of changes. These changes are small enough to avoid nonconformance but large enough to gradually establish (1) what variables are important and (2) the optimum process values for these variables. Although this approach is slower than a formal experimental design, results are achieved in a production environment without the additional costs of a special experiment.

The steps are:

1. Select two or three independent process variables which are likely to influence quality. For example, time and temperature were selected as variables affecting the yield of a chemical process.
2. Change these steps according to a plan (see Figure 3.11). This diagram shows the *plan*, not any data. For example, a reference run was made with the production process set to run at 130°C for three and a half hours. The

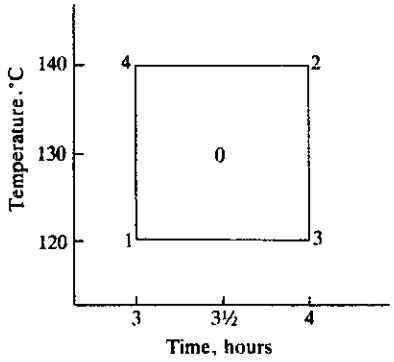

FIGURE 3.11
An EVOP plan. Numbers are in run order. "0" is the reference run.

next batch (point one in Figure 3.11) was run at 120°C for three hours. The first *cycle* contains five runs, one at each condition. Samples were taken from each batch and analyses were made.

3. After the second repetition of the plan (cycle 2) and each succeeding cycle, calculate the effects (see QCH4, page 26.31).
4. When one or more of the effects is significant, change the midpoints of the variables and perhaps their ranges.
5. After eight cycles, if no variable has been shown to be effective, change the ranges or select new variables.
6. Continue moving the midpoint of the EVOP plan and adjust the ranges as necessary.
7. When a maximum has been obtained, or the rate of gain is too slow, drop the current variables from the plan and run a new plan with different variables.

EVOP is a highly structured form of production experimentation. Ott and Schilling (1990) present a varicty of practical design and analysis techniques for solving production quality problems.

Simulation experiments. From the field of operations research comes a technique called *simulation* that can be useful in analyzing quality problems. Simulation provides a method of studying the effect of a number of variables on a final quality characteristic—but all of this is done on paper without conducting experiments! A simulation study requires the following inputs:

1. Definition of the output variable(s).
2. Definition of the input variable(s).
3. Description of the complete system relating the input and output variables.
4. Data on the distribution of each input variable; thus variability is accepted as inherent in the process.

In simulation, a system model is developed and translated into a computer program. This program not only defines the relationship between input and output variables but makes provision for storing the distribution of each input variable. The computer then selects values at random from each input distribution and combines these values, using the relationship defined, to generate a simulated value of the output variable. Each repetition of this process results in a simulated output result. These can then be formed into a frequency distribution. The payoff is to make *changes* in the input variables or the relationships, run another simulation, and observe the effect of the change. Thus the significance of variables can be evaluated on paper, providing one more way of evaluating theories on causes of problems.

Simulation has been applied to many quality problems, including interacting tolerances, circuit design, and reliability.

Test of Theories of Worker-Controllable Problems

Diagnosis of human errors reveals that there are "multiple species" of error. To illustrate these species, Table 3.8 shows the distribution of 80 errors made by six office workers engaged in preparing insurance policy contracts.

There were 29 types of errors, and they follow the Pareto principle. Notice the data for error type 3. There were 19 of these, and worker *B* made 16 of the 19. The table also shows the rest of the work done by worker *B*. Except for error type 3, *B* made few errors. There is nothing basically wrong with the job specification or the method, since the other five workers had little or no trouble with error type 3. There is nothing basically wrong with worker

TABLE 3.8
Matrix of errors by insurance policy writers

	Policy writer						
Error type	A	B	C	D	E	F	Total
1	0	0	1	0	2	1	4
2	1	0	0	0	1	0	2
3	0	(16)	1	0	2	0	(19)
4	0	0	0	0	1	0	1
5	2	1	3	1	4	2	(13)
6	0	0	0	0	3	0	3
⋮							
27							
28							
29							
Total	6	(20)	8	3	(36)	7	80

B except for defect type 3. It follows that worker *B* and no one else is misinterpreting some instruction, resulting in that cluster of 16 errors of type 3.

Error type 5 is of a different species. There is a cluster of 13 of these, and all the workers made this error, more or less uniformly. This suggests some difference in approach between all the workers on the one hand and the inspector on the other. Such a difference is usually of management-controllable origin, but the reality can soon be established by interviews with the respective employees.

Notice also the column of numbers associated with worker *E*. The total is 36 errors, the largest cluster in the table. Worker *E* made nearly half the errors for the entire team, and that worker made them in virtually all error categories. Why did worker *E* make so many errors? It might be any of a variety of reasons, e.g., inadequate training, lack of capacity to do such exacting work, etc. Further study is needed, but it might be easier to go from symptom directly to remedy—find a less demanding job for that worker.

Thus, this one table shows the presence of multiple species of worker error. The remedy is not as simplistic as "motivate the worker." Understanding these species through diagnosis is important in identifying causes. The great majority of worker errors fall into one of three categories: inadvertent, technique, and conscious. Table 3.9 shows the interrelationship among the

TABLE 3.9
Interrelationship among error pattern, likely subspecies of worker error, and likely solution

Pattern disclosed by analysis of worker error	Likely subspecies of error causing this pattern	Likely solution
On certain defects, no one is error-prone; defect pattern is random.	Errors are due to inadvertence.	Error-proof the process.
On certain defects, some workers are consistently error-prone while others are consistently "good."	Errors are due to lack of technique (ability, knowhow, etc.). Lack of technique may take the form of secret ignorance. Technique may consist of known knack or of secret knowledge.	Discovery and propagation of knack. Discovery and elimination of secret ignorance.
Some workers are consistently error-prone over a wide range of defects.	There are several potential causes: Conscious failure to comply with standards Inherent incapacity to perform this task Lack of training	Solution follows the cause: Increase motivation Transfer worker Supply training
On certain defects, all workers are error-prone.	Errors are management-controllable.	Meet the criteria for self-control.

error pattern, the likely subcategory, and the likely remedies. The three categories are examined below.

INADVERTENT ERRORS. Inadvertent errors are those which workers are unable to avoid because of human inability to maintain attention. Centuries of experience have demonstrated that human beings are simply unable to maintain continual attention.

The usual examples involve a component omitted from an assembly or a process adjustment that is set incorrectly. Unusual examples also occur. Some stockbrokerage companies maintain a special account to cover expenses in connection with errors made in trading stock, e.g., purchase of the wrong stock because of a similarity in the acronyms used to identify companies. In the athletic arena, a football game may be lost because, on a key play near the end of the game, a player mistakenly hears a play called as "green" instead of "three." He misses his defensive assignment, and the opposing team scores a touchdown.

Diagnosis to identify errors as inadvertent is aided by understanding their distinguishing features. They are:

- Unintentional. The worker does not want to make errors.
- Unwitting. At the time of making an error, the worker is unaware of having made it.
- Unpredictable. There is nothing systematic as to when an error will be made, what type of error will be made, or which worker will make the error. As a consequence of this unpredictability, the error pattern exhibits randomness. *A set of data which shows a random pattern of worker error suggests that the errors are inadvertent.* The randomness of the data may apply to the types of errors, to the persons who make errors, and to the times when the errors are made.

Remedies for inadvertent errors involve two approaches:

1. Reducing the extent of dependence on human attention. The tools used here are all of the error-proofing type: fail-safe designs, validation of processes, countdowns, redundant verifications, cutoffs, interlocks, alarm signals, automation, robots. Large reductions in errors can result from the use of bar codes to help identify items.
2. Making it easier for human beings to remain attentive. Examples of remedies are reorganization of work to reduce fatigue and monotony, job rotation, and use of sense multipliers, templates, masks, and overlays.

TECHNIQUE ERRORS. These errors arise because the worker lacks some essential technique, skill, or knowledge needed to prevent the error from

happening. Diagnosis to identify errors due to technique is aided by understanding their features. They are:

- *Unintentional.* The worker does not want to make errors.
- *Specific.* Technique errors are unique to certain defect types—those types for which the missing technique is essential.
- *Consistent.* Workers who lack the essential technique consistently make more defects than workers who possess the technique. This consistency is readily evident from data on worker errors.
- *Unavoidable.* The inferior workers are unable to match the performance of the superior workers because they do not know "what to do differently."

Discovery of the existence of technique errors makes use of the diagnostic tools for worker errors, as illustrated here in the assembly of shotguns.

The gun assembly case. Guns were assembled by 22 skilled craft workers, each of whom assembled a complete gun from bits and pieces. After a safety test, about 10 percent of the guns could not be opened up to remove the spent cartridge—a defect known as "open hard after fire." For such defects, it was necessary to disassemble the gun and then reassemble it, which required about 2 hours per defective gun—a significant waste.

After an agony of fruitless discussion, it was clear that the missing element was factual information. Data already in the files by assembler and time were collected and arranged in a matrix (Table 3.10). Some helpful information became evident:

1. There was a wide month-to-month *departmental* variation in the defect rate, ranging from a low of 1.8 percent in January to a high of 22.6 percent in February. Since all workers seemed to be affected, this variation must have had its cause outside of the department. (Subsequent analysis confirmed this.)
2. The ratio of the five best performances to the five worst showed *a stunning consistency.* In each of the 6 months, the five worst performances add up to an error rate which is at least ten times as great as the sum of the five best performances. There must be a reason for such a consistent difference, and it can be found by studying work methods—the techniques used by the respective workers.

The knack. The study of work methods showed that the superior performers used a file to cut down one of the dimensions on a complex component; the inferior performers did not file that component. This filing constituted a "knack"—a small difference in method which accounts for a large difference in

TABLE 3.10
Matrix analysis

Assembly operator rank	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
1	4	1	0	0	0	0	5
2	1	2	0	5	1	0	9
3	3	1	0	3	0	3	10
4	1	1	0	2	2	4	10
5	0	1	0	10	2	1	14
6	2	1	0	2	2	15	22
17	18	8	3	37	9	23	98
18	16	17	0	22	36	11	102
19	27	13	4	62	4	14	124
20	6	5	2	61	22	29	125
21	39	10	2	45	20	14	130
22	26	17	4	75	31	35	188
Total	234	146	34	496	239	241	1390
% defective	10.6	6.6	1.8	22.6	10.9	11.0	10.5
5 best	9	6	0	20	5	8	48
5 worst	114	62	12	265	113	103	669
Ratio	13	10	∞	13	23	13	14

results. (Until the diagnosis was made, the superior assemblers had not realized that filing greatly reduced the incidence of defects.)

Usually the difference in worker performance is traceable to some superior knack used by the successful performers to benefit the product. In the case of the gun assemblers, the knack consisted of filing one component. In some cases, however, the difference in worker performance is due to unwitting *damage* done to the product by the inferior performers.

There is a useful rule for predicting whether the difference in worker performance is due to a beneficial knack or to a negative knack. Who are in the minority? If the superior performers are in the minority, the difference is probably due to a beneficial knack. If the inferior performers are in the minority, the difference in performance is probably due to a negative knack.

Summary of technique errors. The sequence of events to identify, analyze, and remedy technique errors is:

1. For the defect types under study, create and collect data which can disclose any significant worker-to-worker differences.
2. Analyze the data on a time-to-time basis to discover whether consistency is present.

3. Identify the consistently best and consistently worst performers.
4. Study the work methods used by the best and worst performers to identify their differences in technique.
5. Study these differences further so as to discover the beneficial knack which produces superior results or the negative knack which is damaging the product.
6. Bring everyone up to the level of the best through appropriate remedial action such as:
   (*a*) Training inferior performers in use of the knack or in avoidance of damage.
   (*b*) Changing the technology so that the process embodies the knack.
   (*c*) Error-proofing the process in ways which require use of the knack or which prohibit the technique which is damaging to the product.

CONSCIOUS ERRORS. Diagnosis to identify errors as conscious is aided by understanding their features. They are:

- *Witting.* At the time of making an error, the worker is aware of it.
- *Intentional.* The error is the result of a deliberate intention on the part of the worker.
- *Persistent.* The worker who makes the error usually intends to keep it up.

The outward evidence of conscious errors is likewise unique. Whereas inadvertent errors exhibit randomness, conscious errors exhibit consistency, i.e., some workers consistently make more errors than others. However, whereas technique errors are typically restricted to those defect types which require some special knack, conscious errors tend to cover a wider spectrum of defect types. Knowing these types is helpful in diagnosing errors as conscious.

Management-initiated conscious errors. Many "conscious" errors are management initiated. The most common examples arise from the multiple standards which all managers must meet—cost, delivery, and productivity, as well as quality. Because of changes in the marketplace, managers keep shifting their priorities; e.g., in a seller's market, delivery schedules will prevail over some quality standards. The pressures on the managers are then transmitted to the work force and can result in conscious violation of one standard in order to meet another.

Worker-initiated conscious errors. Some conscious errors are worker initiated. Workers may have real or fancied grievances against the boss or the company. They get their revenge by not meeting standards. A few become rebels against the whole social system, and they use sabotage to show their resentment. Some of the instances encountered are so obviously antisocial that no one—not the fellow employees, not the union—will defend the actions.

Some conscious errors *seem* to be worker initiated but have their origin in inadequate communication by management. For example, three product batches fail to conform to quality characteristic X. In each case, the inspector places a hold on the batch. In each case, the Material Review Board concludes that the batch is fit for use and releases it for delivery. However, neither the production worker nor the inspector is told why. Not knowing the reason, these workers may conclude that characteristic X is unimportant. That sets the stage for unauthorized actions.

Remedies for conscious errors. Generally, the remedies listed here emphasize securing changes in behavior without making any special effort to secure a change in attitude. Either way, the approach is oriented primarily to the persons rather than to the "system"—the managerial or technological aspects of the job. Possible remedies include:

- Explaining the impact of the error on internal or external customers
- Establishing individual accountability
- Providing a balance between productivity and quality
- Conducting periodic audits
- Providing reminders to workers about specific defects
- Improving communication between management and workers on quality issues
- Creating competition and incentives
- Error-proofing the operation
- Reassigning the work

For elaboration on these remedies, see QCH4, pages 22.60–22.61.

Next, we consider the development of remedies in general for both management-controllable and worker-controllable problems.

3.11 PROVIDE A REMEDY AND PROVE ITS EFFECTIVENESS

Following diagnosis to determine the cause, the next step in the breakthrough process is to choose a remedy.

Choice of Alternatives

The diagnostic journey may lead to a wide variety of dominant causes of the symptoms: weakness in the design, inadequacy in a process, etc. Remedial action responds to the findings of the diagnosis. An essential criterion is that both company costs and customer costs be optimized.

In quantifying company costs, the cost impact for each alternative should be calculated on a companywide basis. Included should be the impact on the

cost of poor quality, materials usage, facilities usage, energy consumption, etc. The project team, rather than any one department, is best suited to make this evaluation.

Similarly, the impact on customers' costs and well-being should be evaluated for each alternative remedy. Of particular concern is a remedy that results in perfectionism, i.e., adding cost without adding value.

Rare but Critical Defects

Some defects or errors occur at a low frequency but have a serious effect when they do occur. These "rare but critical" defects demand a special approach. Such approaches include increased design margins (e.g., designing for higher stress levels than expected), increased severity of test conditions, significantly lower variability than allowed by specifications, automated 100 percent inspection, and redundant 100 percent inspection. For elaboration, see QCH4, page 22.63.

Proving Effectiveness of the Remedy

Before a remedy is finally adopted, it must be proven effective. Two steps are involved:

1. Preliminary evaluation of the remedy under conditions that simulate the real world. Such evaluation can make use of a "paper" reliability prediction, a dry run in a pilot plant, or the testing of a prototype unit. But these preliminary evaluations have assumptions that are never fully met, e.g., the prototype unit is assumed to be made under typical manufacturing conditions, when actually it is made in the engineering model shop.
2. Final evaluation under real-world conditions. There is no substitute for testing the remedies in the real world. If the remedy is a design change on a component, the final evaluation must be a test of the redesigned component operating in the complete system under field conditions; if the remedy is a change in a manufacturing procedure, the new procedure must be tried under typical (not ideal) factory conditions; if the remedy is a change in a maintenance procedure, the effectiveness must be demonstrated in the field environment by personnel with representative skill levels.

Finally, after a remedy is proven effective, an issue of communication remains. A remedy on one project may also apply to similar problems elsewhere in an organization. It is useful, therefore, to communicate the remedy to (1) others who may face similar problems and (2) those responsible for planning future products and processes. In one approach, the remedy is entered into a data base that can easily be examined by means of key words.

3.12 DEAL WITH RESISTANCE TO CHANGE

Various objections to the remedy may be voiced by different parties, e.g., through delaying tactics or outright rejection of the remedy by a manager, the work force, or the union. "Resistance to change" is the usual name. Change consists of two parts: (1) a technological change; (2) a social consequence of the technological change.

People often voice objections to technological change, although the true reason for their objection is the social effect. Thus, those proposing the change can be misled by the objections stated. For example, an industrial engineer once proposed a change in work method that involved moving the storage of finished parts from a specific machine to a central storage area. The engineer was confused by the affected worker's resistance to the new method. The method seemed to benefit all parties concerned, but the worker argued that it "would not work." The supervisor was perceptive enough to know the true reason for resistance—the worker's production was superb, and many people stopped at his machine to admire and compliment him. Who would want to give up that pleasure? To cite another example, some design engineers resist the use of computer-aided design (CAD), claiming that the technology is not as effective as design analysis by a human being. The real reason, for some older designers, may include the fear of having difficulty adapting to CAD. To achieve change, we must:

- Be aware that we are dealing with a pattern of human habits, beliefs, and traditions (culture) that may differ from our own
- Discover just what will be the social effects of the proposed technological changes

Based on the scars of experience, some rules can be identified for introducing change.

Rules of the Road for Introducing Change

Important among these are:

- *Provide for participation.* This is the single most important rule for introducing change. To do it effectively means that those who are likely to be affected by the change should be members of the project team in order to participate in both diagnosis and remedy. Lack of participation leads to resentment, which can harden into a rock of resistance.
- *Establish the need for the change.*This should be done in terms that are important to the people involved rather than on the basis of the logic of the change.

- *Provide enough time.* How long does it take the members of a culture to accept a change? They must take enough time to evaluate the impact of the change and find an accommodation with the advocates of the change. Providing enough time takes various forms:
  (*a*) *Starting small.* Conducting a small-scale tryout before going "all out" reduces the risks for the advocates as well as for the members of the culture.
  (*b*) *Avoiding surprises.* A major benefit of the cultural pattern is its predictability. A surprise is a shock to this predictability and a disturber of the peace.
  (*c*) *Choosing the right year.* There are right and wrong years—even decades—for a change.
- *Keeping the proposals free of excess baggage.* Avoid cluttering the proposals with extraneous matters not closely concerned with getting results. The risk is that debate will get off the main subject and onto side issues.
- *Working with the recognized leadership of the culture.* The culture is best understood by its members. They have their own leadership, and this is often informal. Convincing the leadership is a significant step in getting the change accepted.
- *Treating people with dignity.* The classic example is that of the relay assemblers in the "Hawthorne experiments." Their productivity kept rising, under good illumination or poor, because in the laboratory they were being treated with dignity.
- *Reversing the positions.* Ask the question: What position would I take if I were a member of the culture? It is even useful to get into role playing to stimulate understanding of the other person's position.
- *Dealing directly with the resistance.* There are many ways of dealing directly with resistance to change:
  (*a*) Trying a program of persuasion
  (*b*) Offering a quid pro quo—something for something
  (*c*) Changing the proposals to meet specific objections
  (*d*) Changing the social climate in ways which will make the change more acceptable.
  (*e*) Forgetting it; there are cases in which the correct alternative is to drop the proposal

Dealing with resistance to change will always be an art. There are, however, some approaches that provide a methodical way of (1) understanding the impact of change and (2) resolving differences among the parties involved. One approach to understanding the impact is to identify the restraining forces and the driving forces for change ("force field analysis"). Another approach to resolving differences focuses on having the parties clearly state their positions

to identify the exact areas of disagreement (see QCH4, pages 22.39 and 22.68, for elaboration).

3.13 INSTITUTE CONTROLS TO HOLD THE GAINS

The final step in the breakthrough sequence is holding the gains so that the benefits of the breakthrough will continue on and on. Three steps are essential:

1. Providing the operating forces with a process capable of holding the gains under operating conditions. Sometimes this involves minimal change; other times, the process change may be complex.
   To the extent which is economic, the process changes should be designed to be *irreversible.* For example, changing from hand insertion of components for printed circuit boards to automatic insertion by programmed tape rolls illustrates an irreversible remedy. In wave soldering, a remedy which requires a different specific gravity for a flux could be reversible because contamination or other factors may result in a flux having a specific gravity that was previously unacceptable.
2. Establishing operating procedures and training the operating forces to use the new procedures and to meet the standards. In conducting this training, it is helpful to make use of information collected during diagnosis to help explain the reasons for the change.
3. Providing a systematic means for holding the gains—the process of *control.* Control during operations is done through use of a feedback loop—a measurement of actual performance, comparison with the standard of performance, and action on the difference. Elaboration of the concept of control is discussed in Chapter 5, "Control of Quality"; Chapter 17, "Statistical Process Control," explains a collection of statistical process control techniques useful in detecting out-of-control conditions. Chapter 16 describes process audits as a means of verifying the presence of the required process conditions and other remedial steps.

SUMMARY

- The quality improvement process addresses *chronic* quality problems.
- The project-by-project approach uses a sequence of steps to solve chronic quality problems.
- "Proving the need" helps to convince management that the quality issue needs a new approach.
- "Identifying projects" consists of nominating, screening, and selecting projects.
- "Organizing project teams" involves forming teams of people from multiple departments.

- "Verifying the project need and mission" confirms the importance and scope of the project.
- "Diagnosing the causes" quantifies the symptoms and formulates and tests theories until the causes of the problem are determined.
- "Providing a remedy and proving its effectiveness" supplies the necessary action to remove the cause.
- "Dealing with resistance to change" focuses on the obstacles to implementing the remedies.
- "Instituting controls to hold the gains" ensures that the benefits from the project will continue in the future.

PROBLEMS

3.1. Selwitchka (1980) presents data on 10 types of errors using two measures—frequency and cost:

Type of error	Frequency	Cost ($, DM)
A	960	20,000
B	870	28,460
C	420	375,000
D	210	42,000
E	180	124,300
F	180	9,000
G	60	77,800
H	60	12,125
I	30	9,000
J	30	9,125

Note that the first two columns present a Pareto analysis based on frequency of occurrence. Prepare a second Pareto table based on cost. Comment on the ranking of errors using frequency versus the ranking based on cost.

3.2. Unplanned shutdowns of reactors have been a chronic problem. After much discussion, the consensus—called the "wisdom"—identified "cylinder changes" and "human error" as the primary causes. A diagnostic approach based on facts was instituted. Here are data on the causes of previous shutdowns:

Cause	Frequency
Cylinder changes	21
Human error	16
Hot melt system	65
Initiator system	25
Interlock malfunction	19
Other	23
	169

(*a*) Convert the above data into a Pareto table having three columns: cause, frequency, and percentage of total frequency.

(*b*) Calculate the cumulative frequencies for the table in part (*a*).
(*c*) Calculate the percentage cumulative frequencies. Make a Pareto diagram by plotting percentage cumulative frequency versus causes.
(*d*) Comment about the "wisdom" versus the facts.

3.3. In diagnosing causes, it is helpful to ask "why" not once but several times. Imai (1986) attributes the following example on a machine stoppage to Taiichi Ohno:

Question 1: Why did the machine stop?
Answer 1: Because the fuse blew due to an overload.
Question 2: Why was there an overload?
Answer 2: Because the bearing lubrication was inadequate.
Question 3: Why was the lubrication inadequate?
Answer 3: Because the lubrication pump was not functioning right.
Question 4: Why wasn't the lubricating pump working right?
Answer 4: Because the pump axle was worn out.
Question 5: Why was it worn out?
Answer 5: Because sludge got in.

What is the benefit of repeating "why"? Can you cite a similar example from your own experience?

3.4. Draw an Ishikawa diagram for one of the following: (*a*) the quality level of a specific activity at a university, bank, or automobile repair shop; (*b*) the quality level of *one* important characteristic of a product at a local plant. Base the diagram on discussions with the organization involved.

3.5. The following data summarize the total number of defects for each worker at a company over the past six months:

Worker	Number of defects	Worker	Number of defects
A	46	H	9
B	22	I	130
C	64	J	10
D	5	K	125
E	65	L	39
F	79	M	26
G	188	N	94

A quality cost study indicates that the cost of these defects is excessive. There is much discussion about the type of quality improvement program. Analysis indicates that the manufacturing equipment is adequate, the specifications are clear, and workers are given periodic information about their quality record. What do you suggest as the next step?

3.6. An engineer in a research organization has twice proposed that the department be authorized to conduct a research project. The project involves a redesign of a component to reduce the frequency of failures. The research approach has been meticulously defined by the engineer and verified as valid by an outside expert. Management has not authorized the project because "other projects seem more important." What further action should the engineer consider?

3.7. A company that manufactures small household appliances has experienced high scrap and rework for several years. The total cost of the scrap and rework was