QUALITY AND PRODUCTIVITY IMPROVEMENTS IN THE PRINTED CIRCUIT ASSEMBLY PROCESS THROUGH THE USE OF STATISTICAL QUALITY CONTROL

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CONTENTS

INTRODUCTION

In July, 1982, the Computer Systems Division (CSY) of Hewlett Packard Company began the task of implementing Statistical Quality Control (SQC) in its Manufacturing area. After 13 months of concentrated efforts a number of successful projects have been completed and dramatic gains have been made both in quality and in productivity. This paper will attempt to trace the events leading up to the SQC program, provide a detailed description of the several completed projects, and describe the conditions necessary for successful implementation of a similar program at the reader's own division or company.

In addition a model of SQC project process flow is presented in Appendix A. This model was constructed after observing several successful projects. The detailed description of each step should help guide the new SQC practitioner through the sometimes difficult path that will lead to substantial improvements in quality and productivity.

A brief definition of SQC as used at CSY will help guide the reader through the rest of this paper. The purpose of SQC is to provide a framework to allow an organization to work toward continuous improvements in product and process which will increase customer satisfaction at minimum cost. The tools, which are not described here in detail, include control charts, process flow diagrams, cause-effect diagrams, Pareto charts, and others; the bibliography provides sufficient sources for the reader to acquire the necessary details. The process, which is described in Appendix A, involves the selection of a condition which needs to be changed, collecting and analyzing data, and deciding when a process should be changed to improve results. This paper will not explicitly define the types of changes needed; these are necessarily left to management who, through competent use of these techniques, gains a thorough understanding of their own processes.

HOW CSY GOT STARTED WITH SQC

In March, 1981, Dr. W. Edwards Deming was invited by consulting statistician Dr. Perry Gluckman, on behalf of top HP management, to give a two-day seminar to high-level managers from numerous divisions of the company. The seminar stimulated thinking about SQC in a number of HP divisions, especially CSY Manufacturing. Soon after, Dr. Gluckman was hired to teach an introductory course in SQC to managers in the CSY manufacturing area. He was selected because of his strong background in statistics, his knowledge of Deming's teachings and his prior consulting work at HP and other companies. The 16-hour course covered basic statistics, the red bead probability demonstration, and the use of control charts. Although interest in SQC was high for a short time during and after the course, no significant projects were carried out.

In June, 1982, Gluckman was again hired by CSY manufacturing, this time for a longer term. The objective was to stimulate the workforce to undertake some SQC projects to improve quality. He was to be available one day each week to consult with anyone who felt motivated to begin collecting data and to start a project. He also met informally with various departments to suggest areas to be studied. In the beginning no formal objectives were set for SQC implementation. However, there was a general feeling that it was time to get started, attempt some projects, and see what happened.

ORGANIZATION AND DESCRIPTION OF CSY MANUFACTURING

The mission of CSY Manufacturing is to assemble and test HP3000 general purpose business computers. It is organized into departments as follows:

PC ASSEMBLY. Blank printed circuit (PC) boards and components are assembled using automated and hand loading of components, wave and hand soldering, and various other operations including masking, forming, and assembly of fabricated parts.

PC TEST. Completed PC assemblies are turned on and tested using various types of automated and manual test equipment. Failing and misloaded components, solder defects, and internal board problems are discovered and repaired in this area.

CABLE ASSEMBLY AND TEST. Cables and harnesses, which connect printed circuit boards together inside the system, are assembled using both manual and semi-automated techniques and equipment. Assemblies are tested for continuity and repaired if necessary.

FINAL ASSEMBLY AND TEST. Sub-assemblies and fabricated parts are assembled together to make completed systems which undergo various levels of automated testing. Some repairs are made to defective sub-assemblies in this department; defective sub-assemblies may also be returned to previous manufacturing areas to be reworked.

SUPPORT DEPARTMENTS. Departments which provide support to the production areas include Order Processing, Production Control, Purchasing, Incoming Inspection, Stores, Information Systems, Process Engineering and Production Engineering.

THE WAVE SOLDER PROJECT

Project Set-up.

The first project undertaken was to attempt to measure the quality of solder joints which were being produced by the wave solder process. Problems had been evident for some time as many defective solder joints were being detected in later stages of the manufacturing process. This was occurring even though all soldered boards were inspected and touched up immediately after the wave solder process.

The first step was to present a training class to the operators on the wave solder team. They were given instruction on how to collect data and plot points on X-bar and R control charts. During the training it was emphasized that this was to be a team problem solving effort and that management was firmly comitted to the belief that most defects were caused by problems inherent in the process itself and were not the fault of the operators. It was also emphasized that the operators' responsibility was to help identify problems and that corrective action would be the job of management.

The first task was to decide what would be classified as defects, how these defects would be measured and recorded, and how the data would be plotted for later analysis. The wave solder team, with some help from the QA department, made a list of the defects which had been encountered in the past and made up a check sheet which would allow the data to be recorded. A sample of the check sheet is shown in Figure 1. The check sheet listed the various types of defects that might be found on both the component side and circuit side of the board and spaces were provided for writing in the number of each type of observed defect. A grid was provided so that the location on the board of each defect could also be recorded.

It was decided that a 10% sample of soldered boards would be inspected and data recorded on the check sheets. As each board exited the wave solder process, the operator was instructed to roll a multi-sided die. If the roll was a "7" (probability of 0.1), the board was delivered to an inspector who was instructed to find, classify, and record the defects. The inspectors had received extensive training from the QA department so they could properly identify defective joints.

After recording data for a few days it became clear that the process was severely out of control and that approximately 1.8% (18,000 PPM) of the solder joints were defective.[1] A process engineer was then called in to study the current operating procedures. A matrix was developed which showed the values of

WAVE SOLDER DEFECT CHECK SHEET

INSPECTOR: 27
DATE : 8–25
TIME : 9 A.M.

ASSEMBLY: 47–14
LOT NO. : 6605
ORDER NO: 3215

COMPONENT SIDE

A) SOLDER SPLASH ____
B) RAISED COMPONENTS ____
C) INSUFFICIENT SOLDER 6
D) SOLDER BRIDGES ____
TOTAL 6

			C
			C
			C
C C			C

CIRCUIT SIDE

A) COMPONENT LEAD ____
B) COLD JOINT 1
C) NONWETTING ____
D) SOLDER BALLS ____
E) BLOW HOLES 5
F) ICICLES ____
G) SOLDER BRIDGES ____
TOTAL 6

TOTAL BOTH SIDES 12

	B	E	
E			
		E	E
E			

FIGURE 1. Wave Solder Defect Check Sheet. This shows an example of a completed check sheet. Note that 3 types of defects were observed and that "Insufficient Solder" defects tend to cluster along the edges of the assembly while "Blow Holes" appear to be distributed randomly.

the critical variables such as conveyer speed and solder temperature which could be adjusted for each type of assembly. New operating procedures were then written and displayed. An immediate reduction in defects was noted as the new procedures were put into effect by the operators.

Pareto analysis of the defects then showed that a large number were blow holes and that high defect rates seemed to be associated with certain lots of raw boards. A raw board manufacturing problem was suspected so a meeting was called with the supplier to discuss the problem. The wave solder group decided to begin incoming solderability testing of a sample board from each lot; if the sample showed poor solderability, the supplier was instructed not to ship the lot until the problem could be found and corrected. This procedure eliminated blow holes as a major category of defects. Two months of work and some simple process changes had reduced the defect rate to approximately 2,000 PPM.

Further analysis of the data showed that insufficient solder in the holes was now the major cause of defects. It was observed that most of these defects were associated only with the IC pins attached to the ground plane inside the board; insufficient board temperature was the most likely cause so an experiment was performed. The experiment consisted of running the boards through the pre-heater twice before applying the solder in order to raise the temperature of the internal ground plane. The experiment successfully eliminated the problem; since it was determined that modifying the equipment to increase pre-heat would be difficult, procedures were changed to run boards through the pre-heater twice. Even though this procedure was quite out of the ordinary, the fact that it was developed by the operators themselves helped ensure that it was followed faithfully.

After collecting data on the revised process it was noted that in addition to eliminating the insufficient solder problem, other categories of defects seemed to be lower also. One suggested explanation of the improvement was that since flux was applied before the first pass through the pre-heater, the longer activation time improved the process. At this same time the operators observed that the conveyor occasionally halted briefly and that boards on the conveyor during these halts tended to have more defects. Maintenance was called in and the problem was corrected. Control charts now indicated that defects were less than 100 PPM.

With the significant reduction in defects it was now nesessary to modify the data collection procedure to accumulate more defects before data was plotted. The new procedure was to total the number of defects over 4 boards to make one data point. A question was now raised as to whether the inspectors were really counting all defects. A new procedure was established such that QA received a sample of the inspected boards, re-inspected, collected data, and compared their findings with data on the original check sheets. Their data indicated that the inspection process was accurate.

Push Toward Zero Defects.

As the wave solder team became more expert at collecting and analyzing defect data, a feeling was spreading that achieving a defect-free solder process was possible. However, to accomplish defect-free operation, many small causes would have to be found and eliminated. During the next few months a number of small projects were carried out. Solder rack dimensions were checked and a number of fixtures were either repaired or discarded. Flux density was monitored and a new procedure was instituted to better control the density. Board surface temperature was monitored by attaching thermal probes to the top of the boards as they emerged from the pre-heater. A new tool was developed to check the evenness and width of the flux and solder waves. Data indicated that some IC sockets were not soldering properly so a different type socket was specified by engineering. It was determined that partially loaded assemblies that were sometimes placed on shelves for several weeks awaiting the arrival of backordered parts often had higher levels of defects. A process change was made to reduce lead time by delaying board loading until all components were on hand.

During the month of July, 1983, the defect rate was calculated to be 6 PPM on day shift and 15 PPM on swing shift. The wave solder team is continuing to collect and analyze data so information can be provided to determine how to further reduce the defect level. It appears that gains may be made by studying the automatic insertion cut-and-clinch process and incoming component solderability. Figure 2 shows a monthly summary of the dramatic reduction of solder defects in parts per million.

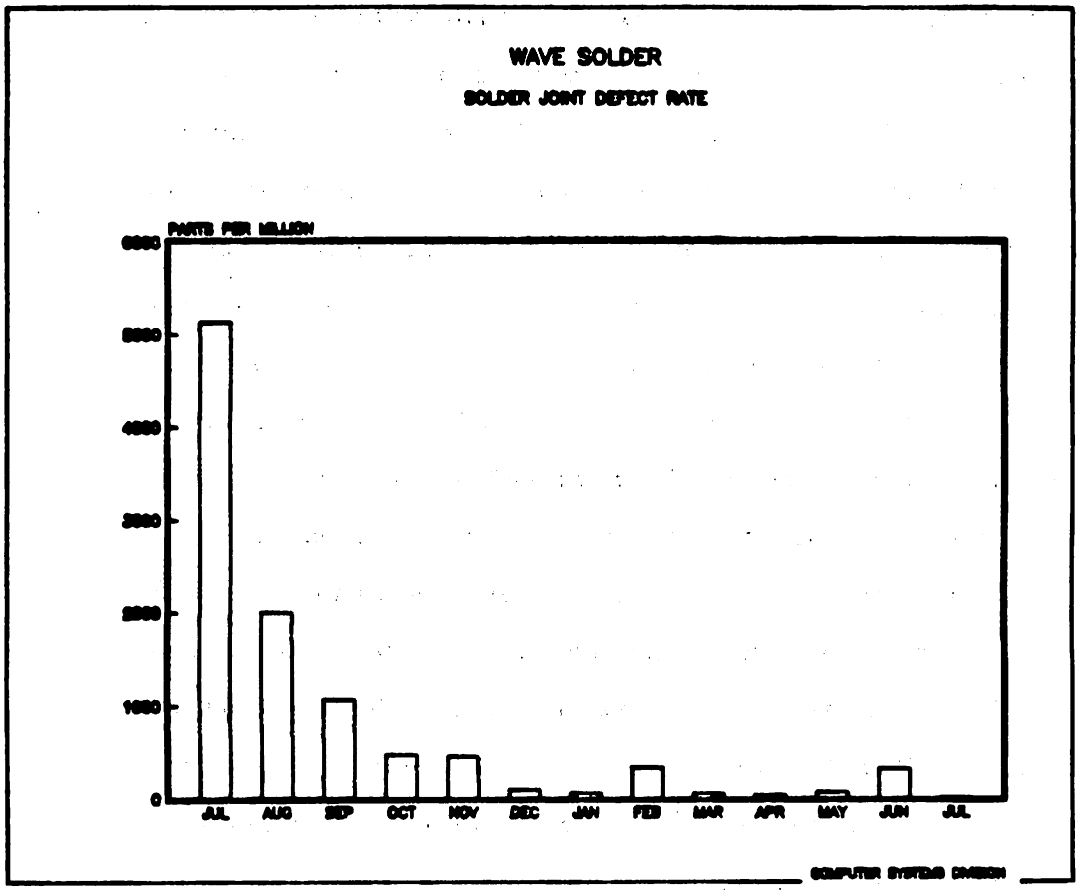

Figure 2. Wave Solder Defect Rate. This shows the dramatic decline of solder defects over a 13-month period. The large increase in June, 1983, was attributed to one lot of boards which had sat unattended on a shelf for several weeks.

Effects of Solder Defect Reduction on Other Operations in the Assembly Process.

A major impact of reduced solder defects was the elimination of Touch-Up as an operation in the assembly process. Previously, soldered boards were returned to an assembly team which was responsible for inspecting the assemblies for poor solder joints, solder balls, solder bridges and other defects. It was left up to each production worker to decide which joints were defective and to take the appropriate corrective action. This operation was considered very difficult and required the most experienced and skilled workers.

This operation itself caused numerous defects including board damage, burned traces, and heat-damaged components. Some of these defects produced scrap in the Touch-Up area while others caused failures and repairs in the Turn-On Test area. Still others undoubtably resulted in expensive warranty failures but no data is currently available to support this. Also, hand soldering left a rosin residue on the IC leads which had to be removed by a special cleaning process so good electrical contact would be made by bed-of-nails test fixtures in the Turn-On area.

After reduction of the defect rate and elimination of the touch-up operation, solder-related defects found in the Turn-On area declined from .05 defects per board to .01 defects per board. It should be noted that the number of defects discovered in the test area was less than those counted by the solder operators because the criteria used by the wave solder inspectors were very tight such that many of these defects were very minor and did not cause electrical failures. After the solder defect level was reduced it was observed that production workers were still performing extensive touch-up to each board! It is probable that the workers felt obligated to find and fix defects, and since they were not well trained in understanding exactly which joints were defective, were repairing good joints. The process was changed to eliminate the Touch-Up operation and standard labor times for board assembly were reduced.

THE AUTOMATIC INSERTION PROJECT.

Process Description.

Another project involving SQC was to study the process of automatic insertion (AI) of dual in-line packaged (DIP) integrated circuits (IC's) onto boards. The equipment in use was an Amistar Model CI1000 automatic inserter which was capable of inserting .300 in. center DIPS. Kits of parts were delivered to the machine and tubes containing 25 IC's were loaded into the 64 stations of the machine. Approximately 10 to 50 boards were loaded in a batch; IC tubes were replaced in the stations as tubes were emptied.

After the components were loaded onto the boards an inspection was performed. A clear plastic sheet had been designed for each assembly; the sheet had the outline of each component and its part number printed on the surface. The inspection process consisted of placing the sheet over the assembled board and visually comparing the markings on each component with the information printed on the plastic sheet.

When mistakes were found, the inspector replaced the incorrect parts. When the project started, no data was being kept by the inspector.

Process Characteristics.

Before SQC techniques were applied to the AI process many operational problems were evident. The machine often malfunctioned and caused parts to be mis-inserted or damaged. The machine operator spent a significant amount of time inserting parts by hand, repairing damaged parts, and clearing jams from the machine. The equipment was often out of service while the maintenance department worked to correct problems. Breakdowns lasting several days were not uncommon while replacement parts were air-shipped from the manufacturer's factory. Often large queues of work-in-process (WIP) were formed and weekend overtime was required to catch up with the workload. The process had been operating as described for approximately two and one-half years.

Implementation of SQC Techniques.

In September, 1982, the supervisor of the AI department embarked on a project to introduce SQC techniques to the process in hopes of improving the situation. With help from Dr. Gluckman and information gained from the wave solder project, a check sheet was developed to provide a means for the operators to begin collecting data on the process. The check sheet listed 12 of the most common problems which had been experienced by the operators. For this project only machine-related problems were studied; problems such as "wrong part inserted" were left for

AUTO INSERTION
DATA COLLECTION SHEET

ASSEMBLY 01-14

QUANTITY 1026

DATE 9-30

PRE-INSERTION DEFECTS QTY. 10

POST-INSERTION DEFECTS QTY.

A. DIP IN MAGAZINE

B. DIP IN SPRING |||

C. STUCK IN SLIDE

D. ROTATOR ~~||||~~

E. FORMER

F. DIE RETRACT

G. STUCK IN JAWS

H. MISSING IC'S

I. DAMAGED/DEFORMED ||

J. BENT LEGS

K. WRONG VALUE

L. REVERSED POLARITY

M. TILTED IC'S

PERCENT OF DEFECTS

A.	%	E.	%	I.	20 %
B.	30 %	F.	%	J.	%
C.	%	G.	%	K.	%
D.	50 %	H.	%	L.	%
				M.	%

Figure 3. Automatic Insertion Check Sheet. Usually, the number of defects counted in a sample of four boards were tallied on each check sheet. In this example 10 defects were recorded out of 1026 components which were inserted.

later analysis. An example of the AI check sheet is shown in Figure 3.

The operators were given some basic instruction in SQC methods and data collection procedures were established. The operators were instructed to roll a multi-sided die immediately before beginning to insert a board. If the die showed a "7" (probability of .1), data on defects would be collected for that board. As each problem was observed by the operator it was tallied in the appropriate category on the check sheet. One check sheet was used to accumulate defect data for 5 assemblies. When the check sheet was complete, the total number of defects for 5 boards was determined and recorded on an X-Bar and R control chart. Data from the check sheets was also summarized using Pareto charts. A sample of the Pareto chart is shown in Figure 4.

After collecting data for a few weeks it was determined that defects were occurring at the rate of approximately 3% (30,000 PPM) and that there was significant variability in the process. Pareto analysis showed that two classes of defects, "DIP Stuck in Spring" and "DIP Stuck in Rotator" accounted for the majority of the defects. Based on this data, two changes to the process were made. First, maintenance was asked to add magazine cleaning and rotator adjustment to their regular semi-monthly preventive maintenance procedures. Second, springs were checked and worn or damaged springs were replaced. After more data was collected it was observed that these two classes of defects noted were significantly reduced.

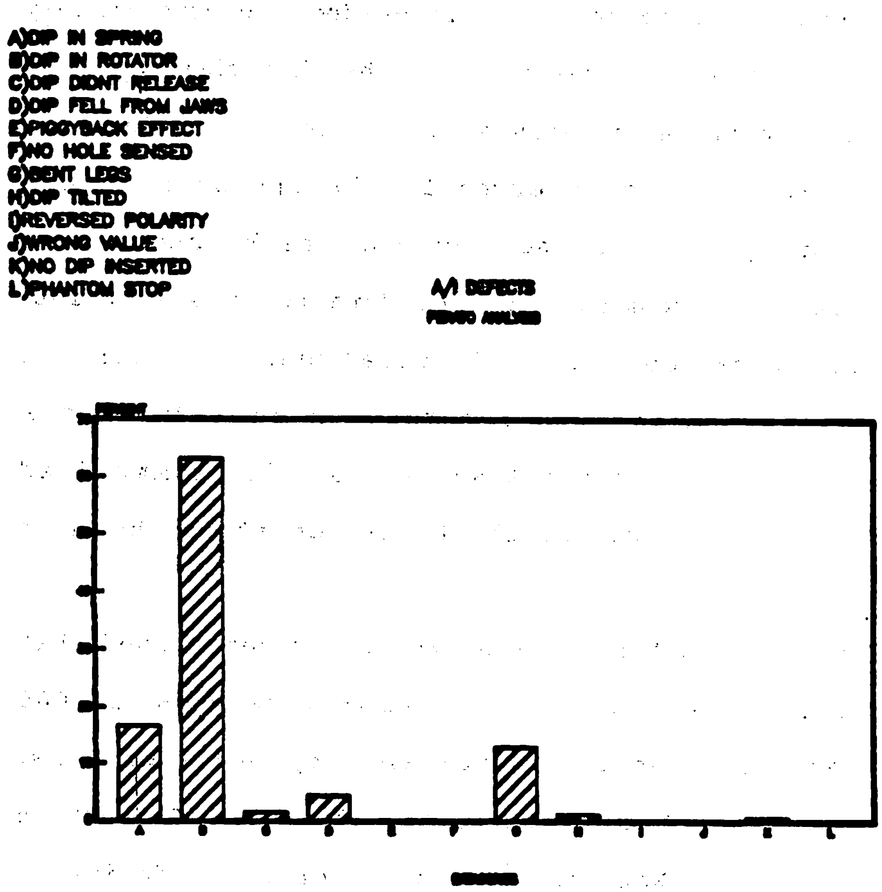

Figure 4. Pareto Analysis of Auto Insertion Defects. Note that in this example more than 60% of the defects wer "Dip Stuck in Rotator".

Data collected for the month of November, 1982, indicated that the major problem was "Phantom Stoppage" of the machine when it was about to insert a DIP. Neither the operators nor the maintenance department were able to determine the cause of this problem. Although greatly reduced, "DIP Stuck in Rotator", was also still a major cetegory of defects. At this point the AI supervisor requested that he be allowed to attend a training class given by the manufacturer of the equipment. During this class he showed the defect data which had been collected and worked with the factory to determine the major cause of "Phantom Stops". It was determined that poor design of the hole sensing unit in the machine was the cause of "Phantom Stops". He also learned that an improved rotator had been designed by the factory and was available to be ordered. Upon returning to the Division, the supervisor modified the sensor unit as instructed by the equipment vendor and the problem of "Phantom Stops" was eliminated. A new rotator assembly was also ordered. After several months of work the mean defect rate was now running at 1.5% (15,000 PPM). Up-time on the equipment was now better than 90%, up from less than 50% at the beginning of the project.

During the months of February and March, 1983, further improvements were made to the equipment based on continued analysis of the defect data. The new rotator assembly was received and installed and a worn-out head assembly was replaced. While watching the insertion operation the supervisor noticed that the boards tended to vibrate rapidly as the insertion head completed each insertion cycle. With assistance from the Tooling department, support tabs were added to the tooling plate to improve board stability. The defect category "Bent IC Legs" was significantly reduced after the addition of the support tabs. During this time a concern was raised that the hole diameters on raw boards might be smaller than specified and could be causing mis-insertions. A study of hole diameters was carried out by the operators which showed the holes to be within specs and slightly oversize which ruled this out as a defect cause. Mis-insertions for March, 1983, were 1.1% (11,000 PPM).

During the next two months a number of adjustments were made to the equipment to further reduce the remaining defects. An improvement was made in the rotator-to-preformer alignment and the rotation chamber was readjusted to ensure an exact 90-degree turn to properly position the DIPS for insertion. One of the major categories of defects was now "DIP Didn't Release". Study of this problem indicated that a modification could be made to the magazine stations which would allow for better travel of DIPS through the stations. The modification was made to all 64 stations and this category of problems was reduced. These actions helped lower the defect rate to approximately .75% (7,500 PPM) for the month of May.

During the month of June it was noticed that a higher than normal defect rate was experienced when plastic and ceramic parts were mixed in the same lot. A combination of adjustments to the interposer and also to the height of the preform chute allowed the machine to insert both types of parts. A milestone was reached as the operators recorded 100% up-time of the machine for the month. It should also be noted that turn-around time for batches of boards processed through the AI department was now less than 5 hours; this figure compares favorably to turn-around average of 20 hours earlier in the project. The defect rate recorded for June, 1983, was .56% (5,600 PPM).

Summary of the AI Project.

During the first nine months of the Auto Insertion project approximately 80% of mis-insertion defects were eliminated from the process. The changes made to reduce defects produced equally dramatic improvements in turn-around and equipment up-time. Also, the working environment was improved for both operators and maintenance people as the management emphasis was on the collection and study of data, not on the blaming of operators and technicians for mis-insertions.

The AI project has not ended; the goal for mis-insertions is zero. The AI team understands that further improvements will come only by their continued study of the process to help guide management in making necessary changes to the process.

THE MATERIAL DISCREPANCY PROJECT

The Discrepancy Problem.

One of the major problems faced by the production workers in the assembly area was finding an effective way of correcting problems in the kits of parts used to assemble printed circuit assemblies. Workers often had to spend a significant amount of time filling out requisitions for missing parts, returning excess parts to stock, and exchanging wrong parts before starting work on a batch of assemblies. It was felt that the application of SQC techniques to the process of assembling kits could help improve the situation.

The Process of Assembling Parts Kits.

The parts storage area had been recently relocated next to the assembly area in order to improve the flow and control of part issues. Daily, Stores received a batch of pull documents for each work order which was scheduled to be pulled the next work day. The batch contained one pull tag for each part type to be included in the work order kit. Kits contained enough parts to build from 5 to 400 printed circuit boards of a particular type; 10 to 20 kits were pulled and assembled on an average day and each kit contained from 10 to 100 different part types with the average being approximately 50.

The process used by Stores began by sorting the pull documents into part number sequence so that multiple quantities of common parts could be pulled at the same time. When pulling was complete, parts were placed in large containers labled with the proper workorder number. Large and expensive parts were counted while small, inexpensive parts were weighed to determine proper quantities. When a workorder kit was complete, an audit was conducted to determine if all the necessary parts were present in the proper quantities. Data was collected during the audit and the indicated error rate for pulling was less than 1%. Completed kits were then delivered to the assembly area.

Data Collection and Analysis.

The first step in the project was to begin collecting data on discrepancy problems found in the assembly area. It was decided that a check sheet would be filled out for each kit as the assembly process was begun. All errors were recorded on the check sheets and an X-Bar and R control chart was begun. Check sheets were accumulated so a summary of error types could be prepared and analyzed.

After the data collection procedures had been in effect for two weeks the control chart indicated that the pulling process was in control and showed an average error count of 1.3 errors per kit with a range of zero to 8 errors. The data indicated that the audit procedure in the Stores area was not effective in screening errors from the assembly area.[2] The data was shown to the Stores group and, after some convincing, they agreed to begin using the new measure, "discrepancies per kit", to determine the quality of the pulling effort.[3]

Since the solution to the problem would involve close cooperation between two departments, a Quality Action Team (QAT) was formed with supervisors from the Assembly and Stores areas.

Discrepancy data was then analyzed by the team and it was observed that the errors could be categorized as "wrong part received", "mixed parts received", "parts not received", "overage received", and "shortage received". The team then brainstormed a list of possible causes for discrepancies; a cause-and-effect diagram showing possible causes is shown in Figure 5.[4]

Various members of the team were then assigned to analyze various parts of the pulling operation and to make recommendations for improvements to reduce errors. One group looked at the weighing process and found that the scale, although very accurate, produced shortages and overages of many parts due to the variation in weights of individual parts in a lot; weighing was also influenced by air currents from the air conditioning system. Several actions were taken to solve these problems including ordering a plexiglass shield for the scale, implementing use of an unused counter-bagger for certain parts and creating a bin stock of frequently-used, low-value parts in the assembly area. The bin stock allowed shortages and overages to be easily corrected in the assembly area; shortages and overages of these low-value parts were no longer counted as errors.

To reduce human error in pulling, part-identification training was provided to stores personnel and sample parts were attached to each bin to help reduce stocking errors. An inexpensive resistor-counter was ordered to improve the accuracy of resistor counts. Data was collected on the accuracy of counts of parts which were pre-bagged by vendors; significant variations were found among vendors including several which consistently

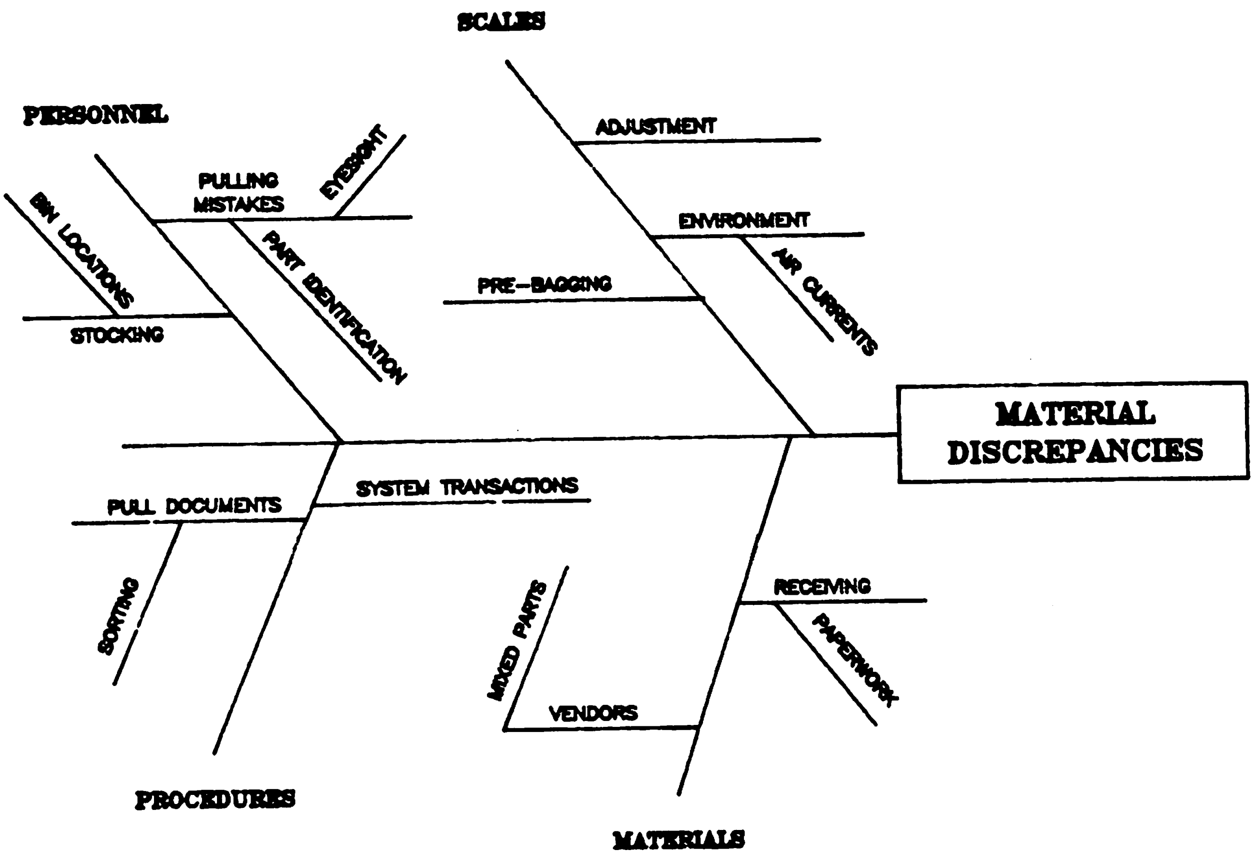

Figure 5. Cause and Effect Diagram Showing Possible Causes of Material Discrepancies. Brainstorming is a good technique for identifying possible causes for a problem such as this.

shipped less than the quantity labeled on the bag. Purchasing was called in to help correct the problem.

Results of the Project.

As improvements were made to the pulling process, the error rate showed a dramatic reduction; after two months the discrepancy rate had dropped from 1.3 errors per kit to less than 0.2 errors per kit. Productivity in the assembly area improved as less time was spent correcting discrepancies. A major improvement was also made in the process of sending kits to a local board assembly subcontractor. Previously, the subcontractor had been allocated 180 square feet near the Stores area to audit kits before they were sent out for assembly; a full-time inspector performed inspection and resolved discrepancies. After being shown the data indicating the improvements in pulling accuracy, the subcontractor agreed to eliminate his inspection procedure. This action improved the subcontracting process and opened floor space for other uses.

Two important conclusions can be drawn from the results of this project. First, significant process improvements can be realized in a short period of time through the use of simple, accurate methods of collecting and analyzing data. Second, a team approach allows adjacent departments to work together to understand each other's processes and make improvements.

CYCLE TIME IMPROVEMENT PROJECT

Printed Circuit Assembly Process.

As favorable progress continued in the areas of reducing defects and errors, an improvement in the work flow was becoming apparent. It was decided that good results might be obtained by studying the overall assembly process to see if the manufacturing cycle time could be reduced; cycle time was defined as the total calendar time elapsed from the time kits of parts were delivered to the assembly area to the time the last tested board in the lot was shipped to the final assembly area. [5] Each kit contained enough materials to assemble approximately one week's usage of each particular type of assembly. Approximately 50 different assemblies were built and quantities varied from as few as 5 for infrequently needed boards to 400 for some high volume types.

The Improvement Process.

The first step in the improvement process was to analyze data that was already being collected to determine how long it was currently taking to complete lots of boards; the standard lead times used in the MRP (computerized material planning and control) system varied from 11 to 15 work days for each board type. Although weekly quantities were used as workorder sizes for all assemblies, lead times were varied by up to 4 days in an attempt to provide some smoothing of the workload. The data indicated that for assemblies which followed the normal flow through the process, the average cycle time was 16 work days with a range of 9 to 36 days. For assemblies that were loaded by subcontractors the average cycle time was 25 work days with a range of 10 to 45 days. The extra time needed for subcontracted assemblies was assumed to be caused by the extra handling and transit time required and the difficulties associated with replacing lost or damaged parts.

The next step was to construct a detailed process flow diagram to show each operation in the assembly and test process. Figure 6 shows the diagram which was constructed for one type of PC board. A circle was included for each separate operation which was performed; a triangle was shown for each shelf or staging area between operations. [6] As there were several possible sequences of operations depending on board type, the assembly with the highest material content was diagrammed first; since this assembly required IC's to be assembled into sockets, and the automatic insertion equipment lacked the capability to insert sockets, the AI operation is not shown for this assembly. It should be noted here that although the entire process required build times of several weeks, only a few hours of direct labor or machine time were actually recorded.

Copies were then made of the process flow diagram so they could be used as data recording sheets. Twice each day, at 9 a.m. and 1 p.m., a supervisor walked through the assembly area and recorded the location in the process of each board on the process flow diagram. Since the cycle time was more than three weeks and 2 to 4 lots of boards were in various stages of assembly at the same time, lot number information was also recorded.

After several weeks of data collection the data was summarized using a "Spencer Diagram" which graphically showed

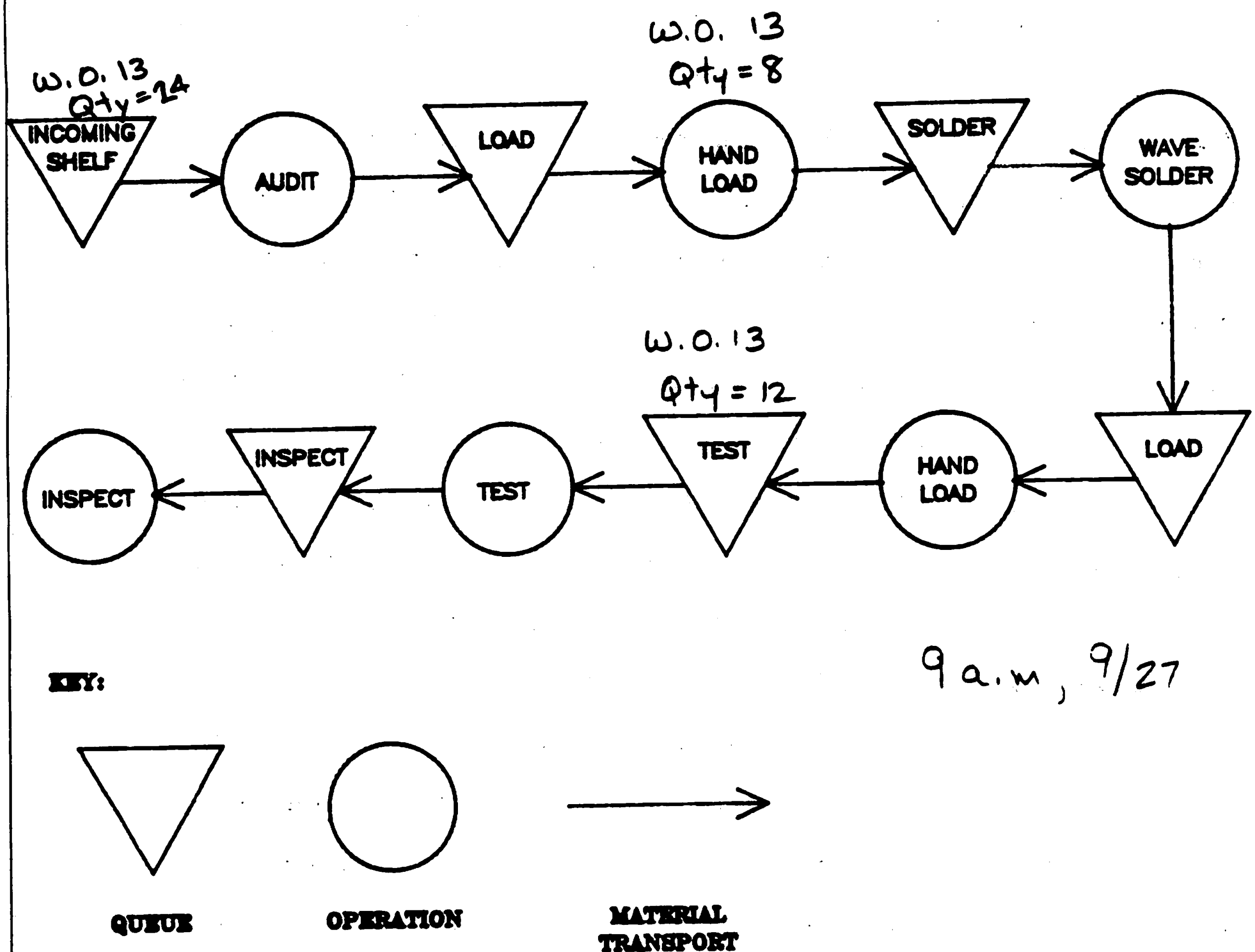

Figure 6. Process Flow Diagram. This example shows the process flow diagram used for data collection. The work order number and quantity of boards found in each step of the process has been recorded. In the example 24 boards from work order number 13 are held in the incoming queue.

the flow of assemblies through the operations over time. [7] A sample of a "Spencer Diagram" is shown in Figure 7. The various operations are arranged along the vertical axis and data collection times are shown across the horizontal axis. Numbers inside the diagram show how many boards were found in each operation. Lines are drawn between pairs of numbers to show the flow of the boards during the previous four hours. The slopes of the lines indicate the relative speed of the flow; steeply sloped lines indicate fast movement through the process. In Figure 7 quantities of boards in queue are noted in triangles; quantities of boards being worked on appear in circles.

Analysis of the data showed that most of the time boards were in queue waiting to be worked on; in fact, in the initial analysis, no boards were ever observed in several of the short-duration operations. The data showed that the entire lot of boards often remained in the initial queue for several days before the first operation was started. It was found that when parts were on back order, no work was performed until the kits were complete, except in cases where the work was late. It was also noted that in one case boards were moved from one queue to another with no operation in between! It could also be seen that although most lots consisted of from 30 to 70 boards, the production workers broke each lot into small quantities of from 4 to 12 boards; these small sub-lots tended to move through the process at varying rates. In several cases sub-lots moved backwards indicating some abnormal condition in the process.

Next, actions were started to make improvements in the process. First, an analysis made of the causes of back orders

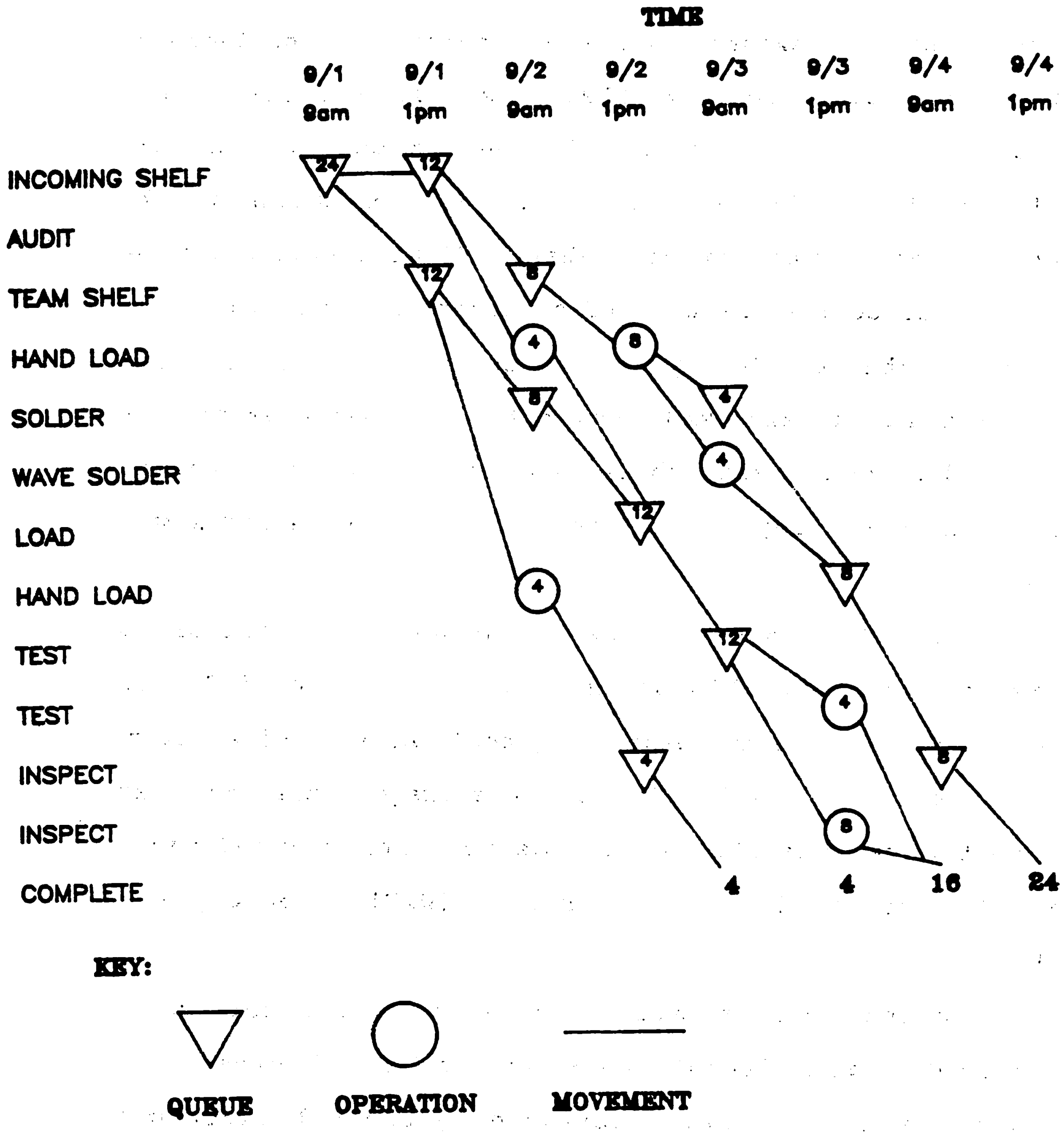

Figure 7. "Spencer Diagram". In this example the boards from this work order were first observed in the incoming queue at 9 a.m. on 9/1. By 1 p.m. on 9/4 all boards had been completed. The total boards observed at each time are equal to 24. Data collected in this manner over many work orders can be summarized to yield an accurate picture of how material flows through the process.

showed that a problem existed in the procedures used for incoming test of random access memory (RAM) IC's. It was found that schedules for this area were not linked directly to the MRP scheduling system. In many cases it was not known by the incoming test department exactly when RAMS were needed by the assembly area so deliveries were often later than expected. It was also found that the IC buyers were not aware of the special procedures which meant that RAMS were often received from vendors too late in the cycle. New scheduling procedures were created and explained to the buyers and the problem of late RAM's was eliminated.

To prevent shortages of other components, a look-ahead procedure was implemented by purchasing so that potential back orders were made visable and expediting could be started earlier. With these new procedures in effect, the average cycle time was reduced to 5 days; the MRP cycle time was then reduced and a significant decrease in work-in-process (WIP) inventory was achieved.

After the reduction in cycle time was achieved, collection of operation data was discontinued; it was then observed that cycle times for the assembly increased by several days, but remained at a level still significantly lower than before. Investigation revealed that while data was being collected the production workers were expediting boards through the process; once data collection was stopped, the workers stopped expediting. The workers were instructed, that when further data was to be collected, no expediting was to be done and boards should be allowed to flow normally through the process.

The results of the initial actions taken to reduce cycle times were summarized and shown to all supervisors and process engineers in the assembly department. Encouragement was given to conduct further studies of the assembly process and to try for further improvements. The group was challenged to work toward reducing average cycle time to less than 24 hours. This aggressive objective was deemed feasible since newly installed wave solder and automatic insertion equipment had increased capacity sufficiently to allow queue reduction in these critical areas.

The new objective for cycle time reduction spurred process improvement activity in all areas of the assembly area. One group suggested that if only complete kits were allowed into the process, significant time could be saved by the production workers. It was pointed out that many lots of boards were partially assembled and then placed on shelves awaiting the arrival of missing parts; in some cases the assemblies were worked on and shelved several times as missing components were gradually received. Another compelling reason to adopt this suggestion was provided by the wave solder team leader who reported that the majority of solder defects for the prior month were found on a lot of boards which had been shelved for several weeks awaiting parts. Possible explanations of increased solder defects were that oxidation was occurring on exposed component leads or that moisture absorbed from the air was interfering with the soldering process.

With all in agreement, Stores was instructed to change their procedures such that only complete kits were delivered to the assembly area. The effects on the assembly process were both dramatic and immediate. A large stack of incomplete kits was formed near the stores area and a tour of this area was arranged for the buyers so they could see the full impact of late materials; they were asked to cooperate with the assembly area to help solve this now visible problem. As incomplete kits were gradually flushed from the assembly area numerous shelves became empty and were dismantled and removed from the area. Several hundred square feet of free space appeared in the assembly area. An immediate improvement in morale and productivity was observed as significant complexity was removed from the assembly process.

The addition of appreciable space allowed several process changes to be tried. A number of operations were combined and workstations were relocated so that less material movement was required. Assembly teams were reorganized so that lots of boards could continue flowing through the process on both day and swing shifts; previously each team had been assigned certain assemblies which meant each type of board could only be worked on during certain hours of the day.

As work-in-process queues were eliminated a problem surfaced: fluctuating amounts of work delivered to the beginning of the process caused frantic activity during some periods and complete inactivity during other periods. [8] The problem was studied by Production Control and the decision was made to reduce lot sizes significantly so that lots of each board type would be delivered several times each week or even daily in the case of high volume assemblies. It also became apparent that the new assembly process could not tolerate significant down time of critical equipment such as the automatic insertion and automatic test equipment. A study was begun to work on ways to reduce the average repair time of each piece of equipment.

The data now showed that a significant reduction in cycle time had been achieved. With the reduction in lot sizes not yet in effect the average cycle time appeared to be in control with a mean of 5.5 days, down from 16.35. Sorting the data by lot size showed that further improvements would be achieved as smaller lots reached the assembly area.

Results and Conclusions.

At the beginning of the project the primary objective of reducing cycle times was to reduce WIP. Although a reduction in WIP was achieved, the unanticipated positive effects should be emphasized. In addition to improved productivity, morale, use of space, and quality, other small gains were noted. The requirements for cardboard tote boxes, mylar protective bags, transfer carts and other supplies related to the amount of WIP were all reduced significantly. The goal of 24-hour cycle time now seems within reach and should be achieved with 6 to 9 months of continued effort.

DISCUSSION OF THE KEY FACTORS NECESSARY FOR SUCCESSFUL IMPLEMENTATION OF STATISTICAL QUALITY CONTROL

Introduction.

The experience of implementing Statistical Quality Control at CSY has made it clear that there are a number of conditions which are favorable to accelerating the implementation process; the absence of one or more of these conditions may hinder the program or halt it completely causing much discouragemnt for the work force. As each point is discussed, an attempt will be made to outline specific actions that we have used in our organization to provide a more fertile climate for growth of an SQC program.

Top Management Must Clearly Understand the Need for Improvement.

Our experience supports the claims of W.E. Deming that if quality is to be improved, top management must feel the need to improve quality and must communicate this feeling to all levels of the organization in order to establish a proper climate for SQC implementation. Gaining an understanding of the rapid progress being made by the Japanese in improving quality should help management internalize this need and feel a sense of urgency.

A prime example of how to get this point across was presented recently at a lecture given by several managers from the HP division based in Japan. The subject of the lecture was a discussion of the program of Total Quality Control (TQC) in use there which had helped them win the coveted annual Deming Prize for quality improvement. The managers were explaining the use of statistics in improving the order closing ratio of their salesmen and used the term "Attack Targets" several times in the presentation. It soon became clear that this term referred to potential customers with whom the salesmen were working! Japanese companies are waging an economic war to expand their market share and are surely studying new markets to penetrate in the United States.

Today, many competent lecturers are available for hire who can present the facts to management; Deming, Perry Gluckman, Philip Crosby, Juran, and William Conway are several who can help establish an urgent need for action in the ranks of top management. Urgency for action must also be communicated to every employee in the organization; it should be stressed that top management will be prepared to provide the proper tools and other incentives necessary to implement a quality improvement program. A detailed implementation program is presented in Crosby's "Quality is Free" and other examples are available.

Management Must Take an Active Role.

Two kinds of support are required from management to implement a successful SQC program. The first, which can be labeled "passive support", can be described as the support necessary to allow the program to proceed. Management must make available competent statistical help who has a thorough understanding of the concepts of SQC and how they can be applied for process improvement. Also, a sufficient budget to cover consulting services, training supplies and materials, meeting rooms, and other needs must be provided. Management must "bless" the program and let the work force know that they support the program and that rewards will be provided to those who are successful in achieving improvements. Passive support is necessary, but not sufficient, to implement an SQC program; active support must also be given generously.

To provide active support a manager should be as thoroughly trained in the principles of SQC as any of his staff and should actively participate in projects as a member of a team. The manager should take an active role in leading training sessions. The manager must show a high level of enthusiasm and ensure his subordinates demonstrate this also. The manager should encourage everyone to circulate copies of control charts, Pareto diagrams, minutes of meetings, and other documents; he should personally make positive comments to the originator of such materials every time they come to his attention.

The manager should make sure that control charts and other quality measures are prominently displayed at every point in the process where data is being collected and projects are being worked on. A good procedure is to walk through the plant several times each week, look at the data that is posted, and talk informally with the work force so an understanding of the problems being faced can be gained.

The manager must be prepared to take immediate action to remedy causes of problems when appropriate data is presented to him. The manager must provide an atmosphere that encourages the workers to identify and report problems without being criticized. The manager must make sure the workers know that he understands that most problems are part of the production process itself and are not the fault of the workers.

One major reason for the success of the program at this division is the heavy involvement managers have in the program. After one year in the process a survey was conducted to measure the number of SQC tools in use and the results are shown in Figure 8. Most managers and supervisors had used two or more SQC tools and nearly three-quarters of them had employees who had also used tools.

Figure 9 shows in more detail the strong motivation of the employees to adopt the use of SQC tools if the supervisor was also using them. Few employees use tools which are not used by their supervisors; most supervisors who have used particular tools have employees who have also used those tools. It is suggested that each manager undertake some project of data collection and analysis to become familiar with the tools available in order to set a good example for his people.

Training Must Be Ongoing and Thorough.

Learning to be proficient at the business of SQC is much like learning to become expert at the game of golf. Just as it is inappropriate to expect a novice who hits long accurate shots off the practice tee with a competent professional at his side to achieve par under course conditions, is it unwise to expect to see immediate and major improvements in quality after giving a two-day course to the work force on how to construct control charts. A long-term program of training must be developed and the concepts be practiced diligently.

The first step in the training should be a short course in basic SQC concepts presented to managers down to the supervisory

Number of SQC Tools Used	Number of Managers
0	1
1	1
2	5
3	3
4	6
5	3
6	4
Total	23

Figure 8. Number of SQC Tools Used by Managers. Of 23 managers surveyed, 22 had used at least one tool and 4 managers had used all six tools covered in the survey.

SQC Tool	Managers Who Have Not Used This Tool: Whose Employees Have Not Used This Tool	Managers Who Have Not Used This Tool: With Employees Who Have Used This Tool	Managers Who Have Used This Tool: Whose Employees Have Not Used This Tool	Managers Who Have Used This Tool: With Employees Who Have Used This Tool
Process Flow	7	-	6	10
Cause-Effect	10	-	3	10
Pareto	6	-	4	13
Histogram	12	-	3	8
Control Chart	3	2	6	12
Scatter Plot	13	2	4	4

Figure 9. Relationship Between The Use Of SQC Tools By Managers And Their Employees. The survey data shows that few employees use tools not used by their manager. The data also shows that a majority of managers who used a particular tool had at least one employee who had also used that tool.

level; other professionals including process engineers should also attend the introductory training. After training the students should be able to construct simple types of control charts and should be able to do some interpretation of the data. The students should also gain a basic understanding of probability theory; the Brown Bead Company Exercise (See Appendix B) has been proven to be an effective method of conveying simple probability concepts and demonstrating the difference between process problems (that can only be removed by management) and problems that the workers have some control over.

Next, participants should be encouraged to pick some condition that they would like to see changed and begin collecting data so a process can be studied; the first attempt should involve a simple process in the working environment such as measuring machine output or counting defects.[9] Examples from the students' personal lives can also be used effectively such as measuring daily body weight, daily commute time or automobile gas mileage. Extensive help may be necessary at this early stage of training to ensure participants are successful.

As the implementation process proceeds, a long-term program of training should be begun so that the initial high level of motivation of the workforce can be maintained; without continuous training, any member of the staff who experiences difficulty with a project may become frustrated and decide to abandon using SQC. An approach to this type of training which has been used successfully at CSY will now be described.

After several months of the implementation process a number of successful projects had been completed as described earlier.

The statistical consultant continued to come to the plant one day each week and anyone who wanted help could arrange for a consultation by reserving time on the consultant's desk calendar. However, it was becoming apparent that the number of active projects was not increasing and was evidenced by the small number of people signing up to talk with the consultant. In order to stimulate further projects the department manager announced that an SQC study group was to be formed and that all supervisors, section managers and process engineers were invited to attend.

It was decided that the study group would read SQC source material together, discuss the concepts presented, and attempt to see if ideas and techniques might be relevant to the processes in the department. The first material selected was QUALITY, PRODUCTIVITY, AND COMPETITIVE POSITION by W. Edwards Deming. This text had been published in late 1982 and was designed to be used with an extensive series of video tapes of Deming's lectures. The group met for one hour each week to discuss what they had learned in the assigned reading. A list of discussion questions had been given the group in advance to stimulate discussion. The group was led by the department manager; the consultant and a resident statistician attended to help with the explanation of the more difficult topics.

As the group progressed in the reading, other materials were added to broaden the content. Video tapes on quality control, guest speakers and original material prepared by the statisticians were all used effectively. Also, each week one member of the staff who was collecting data was invited to show the data and lead a discussion focusing on a description of the process being monitored, whether or not the process was in control, and what further activities were planned.

The weekly sessions often generated lively discussions as the staff discovered that many procedures then in use in the manufacturing area were challenged by statements in the readings. After some six months of classes the level of understanding of the SQC process had increased significantly as could be seen by the fact that some 30 processes were in some stage of analysis. However, even this extensive training had failed to provide nearly half the staff with sufficient skills or motivation to work independantly on projects. It was evident that some members, especially those with little college level training were having difficulty grasping some of the concepts.

It was decided to continue the weekly sessions for at least six more months in order to bring all members up to a common level of understanding. The next material selected for analysis was GUIDE TO QUALITY CONTROL by Kaoru Ishikawa. This is an excellent introduction to a number or simple statistical tools with good discussion on how to use them and numerous exercises which can be worked and discussed. It was also planned to introduce some material on Japanese manufacturing methods as continued process analysis would undoubtably lead to the use of some of these techniques.

In addition to the weekly classes another method of sharing information and increasing motivation was tried. All supervisors, managers, and engineers were invited to a meeting to listen to a discussion of what SQC projects were in progress.

Anyone collecting data was invited to share their experiences in front of this group. Two two-hour sessions were held with good attendance and were considered valuable in promoting SQC concepts to departments which were not currently working on projects. A further benefit was a chance to show management which of the processes needed to be changed and what problems were being encountered.

Positive Rewards for Success Must Exist.

In order to ensure successful implementation of SQC it is vital that positive reinforcement be provided to all participants at each step in the process. It is even more important that participants not be penalized for their activities. First we will undertake a discussion of positive rewards and get to the penalties later.

As is true in stimulating any behavior, positive reinforcement must be given by those in charge of the organization. It has already been pointed out that merely by observing actions taken by the workforce and making positive comments, workers will gain recognition and feel more positive about the process. Managers should also recognize improvements by giving public recognition to teams which have solved problems and by writing articles for company publications which give visibility to participants. Company-sponsored lunches or dinners with managers in attendance will provide long-lasting positive good feelings among the workers. Although workers will be justifiably proud of improvements they have made, there is no substitute for a personal and sincere thank-you from the boss.

Several characteristics of the SQC process can lead to the giving of severe penalties for those who participate in making improvements. In some cases management may be unaware of the negative rewards inferred by the workers for the actions they take. Obviously, workers are not likely to tell management how to do more with less if they or their friends will have to make a painful job transition as a result. People in incoming inspection may be reluctant to collect good data on the quality of parts if they see some of their co-workers forced to change jobs because past data they collected resulted in improvements in quality of incoming parts which reduced the need for inspection. Middle managers should not be rewarded by demotions if their improvements result in a reduction of the size of their departments.

Another problem is the potential loss of visability which can be suffered by a department which has made process improvements. In many organizations managers who are excellent at solving crisis situations receive the majority of top management attention while those who have smooth running processes receive much less attention. A quote from an article written by Charles Quackenbush illustrates this point. He says, "If you spill milk and then try to save it, you are an American results-oriented manager. If you change the process so there is less spilled milk, you are a Japanese process-oriented manager."[10] It is clear that the new way of managing will concentrate on preventing problems before a crisis happens.

A final potential problem is related to the characteristic of SQC analysis to expose previously concealed problems and to search out the causes; if this process causes a problem to be discovered in one organizational area, and the cause happens to be located in another, ill feelings may result toward the group which has exposed the problem. Forming a team to study the data with members of all involved groups before the cause is discovered can sometimes eliminate this problem and lead to better teamwork within the organization; if it is perceived that one department is "pointing fingers" at the other, the effectiveness of an SQC program will be severely reduced. Forming a team with representatives from a supplier who is thought to be supplying poor quality materials or making late deliveries can lead to substantial gains; cooperative study of the data may lead to the discovery that the specifications are in error or the customer has been ordering within lead times.

CONCLUSION

Implementation of SQC at the Computer Systems Division has led to significant improvements in both quality and productivity. We have discussed several case histories of successful projects and tried to explain some of the reasons for the successes. We have also discussed some of the key management factors that need to be present in an organization to stimulate growth of the concepts of SQC.

Proposal for Future Quality Improvements.

We will now propose a three-step program, based on our experiences, which should lead to further gains in quality and productivity.

1) Ensure a Participative Work Environment. A positive environment must be provided for the work force which encourages creativity in analyzing and improving processes.[11]

2) Institute A Program Of Company-wide Quality Control With SQC As A Driving Force.

3) Adopt A "Zero Inventory" Philosophy In The Manufacturing Process.

We feel that a participative work environment is necessary to realize large gains in quality and productivity. Employees must not be afraid to report problems and collect data and must be assured that management will take actions to improve the work. Once that climate is established, SQC and Zero Inventory programs can be used together to produce good results.

From studying the results of these programs at HP and other companies it appears that Zero Inventory programs can achieve good results but must be integrated with a company-wide quality program so that full benefits can be realized.

NOTES

1. For convenience it was decided to measure the number of defects solder joints per million solder joints produced. In this example, and in later ones to follow, defect rates will be referred to as "Parts Per Million" (PPM). This notation was found to be easier to work with than very small percentages. For example, 6 PPM is easier to work with than 0.000006.

2. This is one of the many examples we found of the ineffectiveness of inspection in eliminating errors and defects from production. Deming describes many problems with inspection. He advocates inspection for process surveillance and control, but notes that inspecting to screen out defects is a relatively ineffective and expensive way to obtain quality.

3. In attacking inter-departmental problems the importance of agreeing on a common performance measure must be emphasized. Also, it is preferable the the "customer" or receiver of materials or assemblies have the major say in determining the proper measure. In the material discrepancy case mentioned here, the Stores department measured their performance in terms of the percentage of pulls in error and since their error rate was less than 1%, they considered their performance to be very good. However, since each workorder kit had many part types, nearly two-thirds of all kits received by the assembly area contained at least one discrepancy; clearly, then, this was a situation that needed improvement.

4. For a thorough treatment of cause-and-effect diagrams see Ishikawa, Chapter 3.

5. Note the difference in the use of the term "cycle time" from its meaning in the <u>Toyota Production System</u> and in much of the current literature describing just-in-time production or zero inventory systems. In these cases cycle time refers to the length of time between completion of similar items in the production process; it may be expressed as "25 bearings per minute" or "a car every 72 seconds".

6. In order to construct accurate process diagrams it is important to carefully interview line supervisors and production workers in order to include the informal queues and operations which have been developed to handle production problems encountered in the process. Changing the process without considering the informal operations may not lead to the desired results.

7. I am indebted to Spencer Graves of the Santa Clara Division of the Hewlett Packard Company for constructing the first of these diagrams I have seen which has made the analysis of material flow through complex processes quite simple.

8. As process changes are made which reduce intermediate WIP queues, problems of uneven material flow will be exposed causing production areas to be lightly loaded for varying periods of time. During these periods management should reduce the emphasis on measuring labor variances and machine loading so that attention can be focused on leveling the work flow. In many cases reducing queues will reduce process complexity to improve productivity more than enough to offset idle labor and machine time.

9. See Appendix A for a complete description of the process improvement process.

10. See the Quackenbush article.

11. See Ouchi for a good discussion of the factors necessary to provide this environment.

12. For a thorough discussion of "Zero Inventory" concepts see Zero Inventory Seminar Proceedings.

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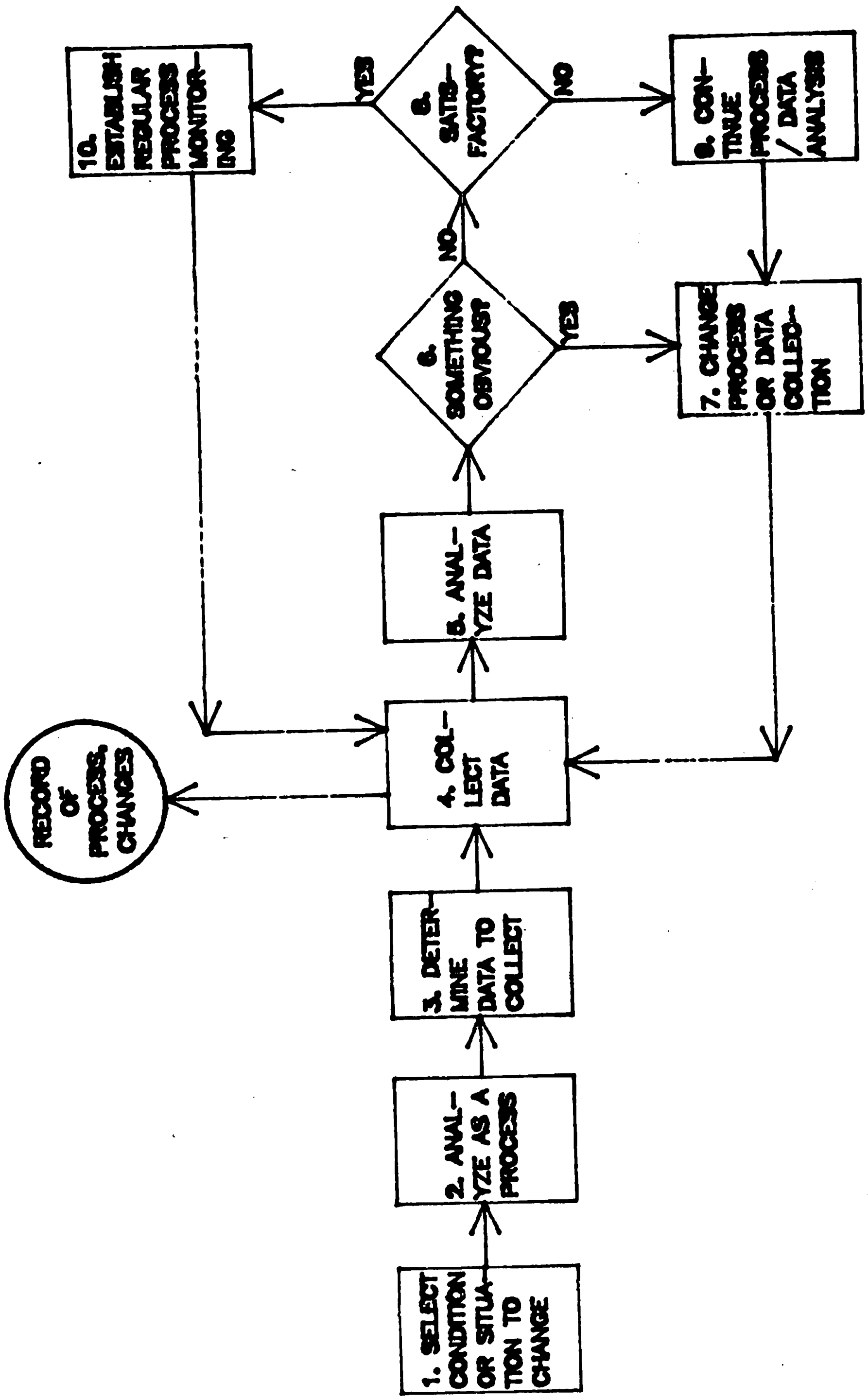
APPENDIX A

PROCESS FLOW DIAGRAM FOR AN SQC PROJECT



Process - Flow
for an
SQC Project

1. Select a situation or condition you want to change.
2. Analyze the operation as a process,
   a. Informally.
   b. Make a process-flow diagram.
   c. Make a cause-effect diagram.
   d. Hypothesize some other kind of model (e.g., relational diagram, algebraic model).
3. Determine what data to collect.
   a. What is unknown that might to useful to know?

	Quality	Quantity	Timing	
Inputs				
Intermediate				
Outputs				

   b. What variables could be measured? What qualities could be quantified or counted?
   c. What could we do with such data if we had it?
      (i) Pareto Diagram
      (ii) Histogram
      (iii) Control Chart
      (iv) other

d. How could we reliably collect such data to get the information we want with minimum work?

(i) Where in the process?

(ii) Using what test or measurement equipment or what kind of qualitative standard? (For example, what constitutes a defect? And how could calibration of test equipment or qualitative standards be maintained?)

(iii) In what format or using what kind of data collection form?

(iv) Who would collect it?

e. Is 100% data collection feasible? If we sample, how do we select the (random) sample?

f. Can we do something simple and sensible now, and change it tomorrow or next week depending on what we learn? (If yes, do it. If no, we must be more careful in thinking about what we want to know and how the data we collect might help us.)

g. Is such data collection feasible?

(i) If no, go back to substep 3.a.

(ii) If yes, proceed to step 4.

4. Collect data to monitor the process over time. Maintain a log of all changes made to the process and the impact these changes had on the data.

5. Analyze data: Make a Pareto diagram, a histogram, a time series plot, a control chart, or ... .

6. If some obvious and easily corrected problem is apparent (e.g., a Pareto analysis or a histogram reveals something obvious, or a control chart has a point or points "out of control," and the reason is obvious), go to step 7. Otherwise, go to step 8.

7. Change the process or data collection. If the indicated change requries the approval or cooperation of others (supervisors, managers, or coworkers), present the change and the data and analysis for their review. Continue with step 4 to see if this change has any impact.

8. Is the Process satisfactory?

a. Is the defect or rework rate too high (relative to the other difficulties we face?)

b. Does a high percentage of the product meet specs?

c. What is the "actual manufacturing cycle time" relative the the scheduled cycle time?

d. What percent of the actual manufacturing cycle time is queue time?

e. How much idle inventory is being maintained?

f. What percent of the time is equipment down for unscheduled maintenance?

If the process is satisfactory, make sure appropriate monitoring is maintained to keep it that way, as described in step 10. Otherwise, continue with step 8.

9. The process is not performing satisfactorily:

a. Continue the process analysis begun in step 2.

(i) Do the data help us isolate a problem? Do they suggest a potentially benificial change in the process? Can that change be implemented at least on an experimental or temporary basis to see if it actually has the desired impact on the process and the data we collect?

(ii) Would a change in the data collection procedures provide better information to help isolate a source of difficulty? Or could the data collection procedures be changed to provide the needed information with less work?

b. Set upon some change either to the process or to the data collection methodology, and continue as in step 7.

10. The process was found to be satisfactory at the moment. To make sure it stays that way, proceed as follows:

a. Review alternative sources for data that would provide reasonable information on the status of the process and would still be easy to collect.

b. Establish (or continue) procedures for regular process monitoring using a control chart based on these data.

c. Continue with step 4.

APPENDIX B

The Brown Bead Manufacturing Company *

Materials: A box containing several thousand small, light-colored beads and a few hundred red beads of the same size. A paddle (See Figure 1) which can be used to draw samples of 50 beads at one time.

Start the exercise by announcing that all participants have been hired to work for the Brown Bead Manufacturing Company, whose primary organizational objective is the manufacture of small brown beads. Show a sample of the company's product line and point out its features to the participants.

Pass out one blank control chart to each participant. You should also have had an overhead transparency made of a blank control chart for your use during the exercise.

Have each participant draw five samples of fifty beads. As each draw is made, have all participants record the number of red beads drawn in the appropriate spot on their control charts. For the purpose of this exercise, approximately 20 sets of data points (100 draws) should be drawn and recorded. As participants record the data points on their control charts, you should also record the data points on the overhead transparency. Interrupt the drawing procedure several times as follows:

1. After the very first draw is made, stop the participant and say something like, "I notice that you have drawn several red beads. How do you feel about that?... Did you know that the objective of this company is to manufacture brown beads, not red beads?... Well, listen. I think that this is probably my fault. I didn't make sure before we started that the objective was really clear to you. But now that we've clarified and reached agreement on the objective, I would look for an improvement in your performance. Do you think you can achieve that?"

Learning Point: Managers can't assume that simple because they have clarified objectives for their employees that they will be more motivated or more able to accomplish a task.

2. After several participants have drawn beads, stop after someone has had a high draw of red beads. Indicate that this is unacceptable and ask a participant who has already drawn and who had a low average of red beads to provide training. Ask the

* This exercise was developed from work done by W. E. Deming, Bill Boller of the Hewlett Packard Company, and Dr. Perry Gluckman.

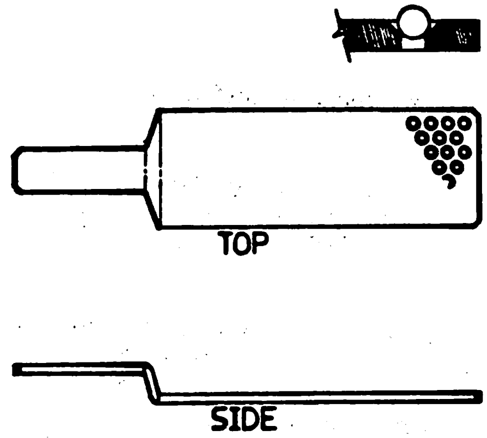


Figure 1. Bead Paddle. The illustration shows a sketch of how a paddle could be constructed. Drill holes slightly smaller than the size of the beads.

participant to show how he or she holds the paddle, how deeply to draw, what motion to use, etc. After training, commit the participant who had drawn a high red bead count to improve.

Learning Point: Training may be powerless to resolve problems which reside in the system.

3. Next, indicate to another participant before he or she begins to draw that you are going to make his or her pay contingent on performance. Offer the person $5 if he or she can achieve an average of "n" (n should be selected such that its probability is .01 or less.) red beads or less for the next five draws.

Learning Point: Pay can also be powerless as a motivator when systems problems exist.

4. After another participant has made two or three draws, threaten to fire him or her if the person draws over three (or some number) red beads in any of his or her remaining draws. Indicate that you're simply going to have to make an example of him or her for producing too many defectives. If more than three red beads are drawn, fire the participant.

Learning Point: When there are problems in the system beyond the control of the employee, management pressure can only be counter productive. Emphasize that 85% of the production process problems that surface are attributable to problems in the system. (Common causes) Only the remaining 15% are caused by employee error. (Special causes) This is Deming's rule of thumb and as he points out, the burden for removing the systemic problems is clearly on the shoulders of management, not the employees.

5. Next, after most of the draws have been made, ask a participant to predict how many red beads will be drawn on each of the next two draws.

Learning Point: No matter how much data is collected, the exact number of red beads cannot be predicted with certainty.

6. Before the next participant begins drawing, ask someone to predict the average number of red beads for the next five draws.

Learning Point: Since each hole has an equal chance of drawing a red bead, the average number of red beads in a draw tends to cluster around a certain number. (This is the central limit theorem).

7. Continue drawing beads and recording the data until approximately 20 sets of data points have been drawn and recorded on the overhead and on participants' control charts. Next, talk about control limits. Ask the group to pick a range within which they expect the average of the next five draws to fall. Try to get the narrowest estimate of a range in which they would feel confident that the average of the next five draws would fall. Then tell them that control limits can be established showing a range within which 99.7% of the averages will fall when the process is in control. The control limits are derived by establishing a center line which is the average of all the averages plotted and then by moving three standard deviations in both directions away from the center line.

Learning Point: Setting control limits can define the capability of the process and serve as an indicator of when the process is out of control and the cause investigated.

At this point have the group plot each of the data points on their control charts, plotting both the averages and the range. Then as a group, calculate the upper and lower control limits for both the X-bar and R parts of the chart. Then review the main points made during the exercise.

Now shift the discussion to the participants' on-the-job situation. Ask participants what they consider to be the red beads in their operations. These might include poor parts from a vendor, late deliveries, unclear standards, machine breakdowns, etc. Record the group's ideas on a flipchart and facilitate discussion until all ideas have been shared.