On-Line Distributed Control System Tools for Statistical Process Control (SPC)

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ON-LINE DISTRIBUTED CONTROL SYSTEM TOOLS FOR STATISTICAL PROCESS CONTROL (SPC)

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ABSTRACT

Recent increases in resource costs and global competition have fostered the spread of a management philosophy called Statistical Process Control (SPC) from discrete manufacturing to continuous and batch industrial processing. Recent advances in microprocessor technology have substantially increased the computing capabilities available within process control systems. Today, computerized Statistical Quality Control (SQC) techniques which were once considered off-line, retrospective support for SPC activities can be used within the context of process control systems as on-line tools to improve the profitability of process operations.

The computing power of a modern microcomputer process controller provides cost-effective SPC tools for critical process parameters. This paper discusses on-line tools for SPC which can be implemented entirely within a distributed digital control system (DCS).

INTRODUCTION

Statistical Process Control (SPC) is based on the fundamental principle that there is a normal, quantifiable level of variation in every process parameter. This normal variation includes both random variation and variation which can be attributed to specific causes. Once the normal process variation is quantified, it can be managed to its most economically favorable level by improving process operations or by modifying the process itself.

Any significant change in process variation from this normal level can be detected and investigated. When a cause for abnormal variation is identified, operations managers can work to eliminate the cause if the abnormal variation is bad, or they can work to perpetuate the cause if the abnormal variation is good.
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If the normal variation of a critical product quality parameter is greater than the tolerance of its manufacturing specification, substantial excess costs will be incurred to test, segregate, and dispose of or recycle off-specification product. On the other hand, excess operating costs may also be incurred by operating the process in a manner that reduces the normal variation of this parameter substantially below the required manufacturing tolerance.

SPC is a management philosophy which seeks to quantify and optimize process variation. Many of the tools for SPC were provided by the pioneering efforts of Walter Shewhart and W. Edwards Deming, which resulted in a group of techniques collectively called Statistical Quality Control (SQC). These techniques are solidly grounded in statistical theory and have been widely applied (REFERENCE 1).

Many of these techniques are best suited to off-line, retrospective analysis of historical process data and cannot be effectively applied as on-line operations tools. However, some SPC tools can be effectively utilized with live process data to provide on-line support for SPC activities:

- On-Line SPC Control Charts,
- SPC Alarms,
- On-line Pareto Analysis,
- Closed-Loop SPC.

These on-line SPC tools collectively alert process operators to abnormal process variation and help identify the cause(s) of this abnormal variation, prioritize corrective actions and manage process variation to its most economical level. Further, they can be implemented easily within a modern DCS.

Many of the off-line, retrospective techniques necessary to fully support SPC activities can also be implemented in modern distributed digital process control systems. The most widely used techniques include cause/effect correlation studies and process capability studies.

THE ECONOMICS OF SPC

Continuous and batch processing operations in a variety of industries provide striking examples of the economic benefits which can result from an effective SPC program. Increased annual profits ranging from $50,000 to $1.4 million are achievable by managing the variation of just one critical process parameter to its optimum.
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A reduction in the variation of the Kappa Number for a continuous pulping operation in the Paper Industry can allow the average Kappa Number to be confidently shifted toward the most economical limit of the manufacturing specification. The Kappa Number is the primary quality/yield parameter for this process. Improvements in process operations which reduce the standard deviation in Kappa Number from 2.18 to 1.50, and shift the average Kappa Number from 17.40 to 18.45, will produce a net pulp yield increase of 0.475% (REFERENCE 2). This will result in an additional $410,000/year of profits for a 1000 ton/day pulp mill.

A reduction in the Kappa Number variation for a batch pulping operation in the Paper Industry can also allow the average Kappa Number to be shifted toward the most economical limit of the manufacturing specification. Improvements in process operations which reduce the standard deviation in Kappa Number from 0.88 to 0.67 and shift its average upward slightly can produce an increase of 0.15% in pulp yield. This will result in additional profits totaling $150,000/year for a 640 ton/day pulp mill (REFERENCE 3).

A reduction in the variation of cracking severity for an ethylene cracking furnace operation in the Petrochemical Industry can allow furnace control setpoints to be adjusted to increase selectivity for ethylene. Depending on the circumstances, this can produce additional profits totaling $1.4 million/year for a 500,000 metric ton/year ethylene plant (REFERENCE 4).

The reduction in cutpoint variation for a crude unit operation in the Petroleum Industry can substantially reduce giveaway of more valuable hydrocarbons with less valuable products. This can result in as much a $441,000/year increased profits for a 70,000 barrel/day crude unit (REFERENCE 5).

The reduction in electrical power demand variation for an industrial plant can save more than $50,000/year in power demand penalties (REFERENCE 6). This additional profit would result from avoiding one 0.5 megawatt demand peak over the established billing demand with a $10.00/kilowatt demand charge and a 0.9 forgiving factor.

ON-LINE SPC CONTROL CHARTS

The control chart from SQC has become the basic tool for SPC. There are many different types of control charts (X-BAR/R, X-BAR/S, Cumulative Sum, Exponentially Weighted Moving Average, etc.). However, each provides a visual comparison of the current
variation in a critical process parameter (e.g. the key quality variable for a product) with its short-term and long-term historical variation. SPC relies on the control chart to identify when the current variation in the process parameter is significantly different than it has been historically.

In the context of a continuous or batch processing operation, an SPC control chart is a specific type of time trend for a critical process parameter (X). X may be the result of a periodic laboratory test, a measurement signal from an on-line sensor, the error (difference between setpoint and process variable) of a regulatory control loop, or any other quantifiable characteristic which represents the state of the process at a point in time.

**Shewhart Chart**

One type of SPC control chart, the Shewhart Chart, trends the average (X-BAR) for a subgroup of individual X values and the range (R) of the individual X values within the subgroup (maximum minus minimum). In addition to these SPC variables, the control chart also shows upper control limits (UCL's) for the X-BAR and R trends, a lower control limit (LCL) for the X-BAR trend (the lower control limit for the R trend can be considered zero), the grand average (X-BAR-BAR) of all X values in the database, and the average range (R-BAR) for all subgroups in the database. A typical Shewhart Chart is shown in **FIGURE 1**.

The variation of X-BAR with time is a quantified indication of the long-term variation of the process parameter X. The variation of R with time is a quantified indication of the short-term variation of X. Observing both long-term and short-term variation of a critical process parameter on the same time axis provides useful information about the state of process operations.

For example, if the shift average for an hourly laboratory test (X-BAR) stays relatively constant, but the range of test values throughout the shift (R) is much larger during the third shift, a sampling/testing procedure problem might exist on the third shift. On the other hand, a relatively constant range for the shift test values (R), with a significant change in the shift average (X-BAR) for the third shift might suggest a substantial environmental influence on the process during the third shift which could be automatically compensated for. If X-BAR-BAR slowly increases or decreases over a period of several months, process equipment might be wearing or fouling, or a reagent used for the laboratory test in small amounts may be degrading.
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The control limits utilize a statistical treatment of historical X-BAR and R data to establish the boundaries of "normal" variation in the process parameter. If the value of X-BAR or R falls above a UCL or below an LCL, there is a 99.7% probability that something abnormal has occurred in the process, and the situation should be investigated. In the example of the hourly laboratory test result, if the X-BAR started falling outside the upper control limit on the third shift at about the same time that a new technician rotated into the laboratory for the third shift, the cause of the situation would be clear.

Abnormal Variation

When the process is operating normally, the values of X-BAR and R will randomly vary between the UCL and LCL. If the region between the UCL and the X-BAR-BAR is divided into three imaginary zones of equal width (zones A, B and C, with zone C closest to X-BAR-BAR), and similarly for the region between the LCL and X-BAR-BAR, statistical theory suggests the following:

- 68% of the normal values will fall within the two C zones,
- 28% of the normal values will fall within the two B zones,
- 2.7% of the normal values will fall within the two A zones.
- 0.3% of the normal values will fall above or below the control limits.

An erratic trend on the SPC control chart indicates normal process operation, whereas this same pattern on a typical process control trend display should be cause for alarm. Conversely, if the variation of X-BAR or R becomes nonrandom (e.g. falls outside of the control limits, flattens out, cycles, ramps up or down, consistently stays outside of the C regions, or exhibits some other definite pattern), something within the process has changed significantly and the situation should be investigated immediately.

In addition to simple high/low tests to identify when X-BAR or R is outside of the control limits, a number of pattern tests have evolved to detect nonrandom variation of the process. Identifiable patterns of X-BAR or R within the ABC zones indicate that something is repeatably influencing process operations. Seven of the most common pattern tests are summarized in FIGURE 2.
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On-Line vs. Off-Line

Historically, the magnitude of the computing task required that SPC control charts be prepared off-line, using data collected during the prior week or month. The cost-effective computing and communication capabilities provided with modern distributed digital control systems permit SPC control charts to be updated for presentation to the process operator as the data becomes available.

The SPC control chart shown in FIGURE 1 is an on-line SPC control chart. An on-line SPC control chart can be differentiated from an off-line control chart by the presence of time steps. An off-line control chart generally shows sharp spikes because individual data points are connected with straight lines. An on-line SPC control chart generally shows time steps because the value of X-BAR and R are held constant during sample intervals.

Although an SPC control chart does not specifically identify the cause(s) of a significant change in process operation, it does permit personnel to be alerted to start looking for the cause(s). Diagnosis of the cause(s) for abnormal variation is generally much more efficient while the variation is occurring. Off-line SPC control charts often identify abnormal process variation after it has passed, making diagnosis much more difficult, if not impossible.

The on-line control chart permits process operators to quickly recognize an abnormal operating condition, search for the cause(s) while the condition still exists, and eliminate or perpetuate the condition to increase the profitability of process operations. The net effect of on-line SPC may be as simple as avoiding a long production run of off-specification material which is costly to reprocess, or it may be as complex as shifting the grand average closer to the most economical limit of the manufacturing specification with the confidence that the normal variation of the process will not produce off-specification material.

Adaptive Control Limits

The normal variation of the process may change as a result of long-term operational improvement or degradation. If the control limits for an on-line SPC control chart represent the normal variation observed in the too distant past, they may be either too wide or too narrow for the process as it is currently operating. This condition will result in the operators either not reacting to situations where the current variation is well
beyond the actual normal variation of the process, or reacting to situations where there is no identifiable cause for a change in variation.

To avoid both complacency and false alarms, the computing capabilities of modern DCS controllers can be used to accommodate these gradual process changes by automatically adjusting the control limits for on line SPC control charts. This adjustment can be accomplished by limiting the historical values used in the calculation of the control limits to a specific time horizon (e.g. 84, 28, 14 or 7 days). As process operations improve from an SPC perspective, a reduction in normal variation will narrow the control limits and the grand average will move towards the most economic limit of the manufacturing specification.

SPC ALARMS

The automatic alarming capabilities of modern distributed digital process control systems can also be used to immediately alert the operator to any abnormal process variation. This is especially critical for processes with more than a few SPC control charts to be monitored -- abnormal process variation could go unnoticed for days or weeks without on-line SPC alarms. An SPC alarm can be generated by the DCS just as any other process alarm.

When X-BAR or R falls outside of its control limits, an alarm can be sounded until acknowledged by an operator, and the alarm event can be automatically logged. This type of alarm is called an SPC limit alarm.

When a specific pattern or trend is identified in the X-BAR or R data, this situation can also be automatically alarmed to the operator and logged, with the specific pattern or trend identified. This type of alarm is called an SPC pattern alarm.

Once the cause for either type of SPC alarm has been identified, it can be entered into the operator console database, logged and archived with the rest of the process operating history. This information will be critical to any off-line SPC analysis.

ON-LINE PARETO ANALYSIS

Vilfredo Pareto, a nineteenth century Italian economist, is credited with the well-known 80/20 rule. In an SPC context, this rule predicts that 80% of the abnormal variation in a specific
process parameter will be produced by only 20% of the potential causes. If this were true in a specific case, elimination or control of the correct 20% of the potential causes would eliminate 80% of the abnormal variation in a critical process parameter.

However, the correct 20 may change over time. As more information is collected on the process, different potential causes could emerge as having the most cost impact on process operations. The potential causes in the top 20% category may change with the seasons or with elapsed time since the last maintenance shutdown. As process operations are improved through application of SPC, potential causes of abnormal variation will be eliminated and different potential causes will move into the top 20% category.

The Pareto analysis could be based on the total number of incidents for which a specific cause has been identified. However, to help manage process variation toward its most economical level, the number of incidents assigned to each specific cause is weighted by a relative cost factor for that cause.

The computing capabilities of modern distributed digital control systems permit Pareto analysis to be accomplished on-line each time the cause for an incident of abnormal variation is identified. This Pareto analysis becomes an operations tool when it is used to prioritize investigation of potential causes for current abnormal process variation. In searching for the specific cause of an abnormal variation incident, the operator would first investigate the potential cause(s) with the highest economic impact. This approach will minimize the cost impact of the abnormal variation incident.

A typical on-line Pareto analysis is shown in FIGURE 3. This operator display represents a prioritized listing of the most costly causes for abnormal variation in a specific process parameter. Each potential cause is shown with its relative cost contribution to incidents for which causes have been assigned, and the cumulative percentage of assigned variation which has been accounted for by preceding causes (e.g. 80% for the second cause in a list of 10).

CLOSED-LOOP SPC

The on-line SPC control chart and its associated SPC alarms provide an open-loop operations tool to identify when some action is required due to abnormal variation in a critical process
parameter. Long-term use of these tools may indicate that specific and predictable actions are repeatedly required to eliminate specific incidents of abnormal process variation. When this repeatability becomes apparent, corrective actions can be automated using various techniques.

The types of action that can be taken include starting/stopping a motor, opening/closing a routing valve, initiating an automatic sequence or biasing the setpoint for a regulatory controller. These actions may be triggered if an SPC parameter remains outside of a control limit for more than a preset number of subgroups or has exhibited a specific pattern in the recent past.

OFF-LINE SPC TOOLS

Off-line SQC techniques can be used to enhance the effectiveness of the on-line SPC tools. These techniques provide retrospective analysis of long-term process operating history. Cause/effect correlation studies of historical process data identify when easy-to-measure process variables can be used to manage difficult-to-measure process parameters. Process capability studies with historical process data determine if the process can perform economically inside of manufacturing specification limits without major modification.

Cause/Effect Correlation Study

Several process parameters may significantly affect the variation observed in a critical process parameter, either singularly or by synergistic combination. A cause/effect correlation study attempts to identify a significant historical cause/effect relationship between an X-Y variable pair. In the context of SPC, Y is the critical process parameter (dependent variable) which may vary as a function of an an independent process parameter, X.

An X-Y graph can be made for a suspected cause/effect variable pair using data from one or several years to form a "scatter diagram". If there is a noticeable pattern of data points in this diagram, the relationship can be quantified using any of several regression techniques to define an equation which relates Y to X, and which permits the value of the dependent variable to be predicted from the value of the independent variable(s) with a certain confidence level.
A cause/effect correlation study might indicate that a critical process parameter was influenced considerably by three specific temperatures, two specific pressures and a particular flowrate. With this information, the process control strategy could then be modified to reduce the normal variation of these six process variables, thereby reducing the normal variation of the critical process parameter.

Alternately, a multivariable regression analysis could establish an equation for the critical process parameter based on the value of the six easy-to-obtain process measurements. An inferential control algorithm could then be applied to hold the critical parameter at its most economic value based on the six process measurements.

Process Capability Study

In Statistical Process Control, the "capability" of a process refers to the natural variation of a process parameter when there are no specific causes which can be attributed to the variation. This natural variation is considered totally random and results from unmeasurable and uncontrollable variations in sampling or testing techniques, raw material composition, ambient conditions, etc.

The natural variation of a critical process parameter is quantified by the following procedure:

- The historical control charts for the process parameter are reviewed to identify SPC variables which fall outside of the established control limits.
- All data is eliminated for subgroups which have a specific cause documented for the abnormal variation.
- Process capability limits (alias control limits) are calculated using the edited subgroup data.

If the natural variation of the process is not within the tolerances of the manufacturing specification, it will be very expensive to produce quality product. In this case, the operating practices of the process itself must be re-designed to reduce the natural variation so that it is within the tolerance of the manufacturing specification.

If the natural variation of the process is much less than the manufacturing specification limits, the process can be maneuvered toward the most economical limit of the manufacturing specification without producing significant amounts of
off specification product. However, if the natural process variation is just inside the limits of the manufacturing specification, there is no room for maneuvering to improve the economics of the process -- in this case, serious consideration should be given to modifications which will decrease the natural process variation and pay for themselves through increased process profitability.

ON-LINE SPC WITH A DCS

The data processing, communications and graphic display capabilities necessary for on-line SPC tools exist within modern microcomputer distributed control systems. DCS controller modules can effectively perform the computations for X-BAR, R (or S), X-BAR-BAR, the control limits, SPC alarms and Pareto analyses. These controller modules can transmit this reduced data and alarm messages across the DCS communications network to one or several CRT-based operations consoles for display and historical data storage.

When an SPC parameter falls beyond a control limit or exhibits a specific pattern, the operator will be automatically alerted and the alarm automatically logged, just as with any other process alarm. As specific causes of abnormal variation incidents are identified, they can be entered into an on-line Pareto analysis through a convenient display on the operations console -- this cause information will also be time-tagged and accumulated in the console database for future analysis.

To support future off-line SPC analyses, the data historian capabilities of the operations console can be used to automatically archive the on-line SPC data. The resulting historical database can be manipulated and analyzed with tools resident in the console for long-term cause/effect correlation and process capability studies.

With a DCS implementation, the calculations and alarm processing are distributed throughout the control system. These functions are located in the controller modules which minimize the burden on the DCS communications network. Distribution of the SPC tools brings the same advantages to SPC that distribution of the control functions brings a process control system. In comparison with a centralized computer implementation, these advantages combine to reduce the life-cycle cost of the SPC tools -- the total cost for design, implementation, operation, maintenance, and modification (REFERENCE 7).
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As these tools become critical to the profitable operation of the process, the enhanced reliability provided by the DCS implementation maximizes the availability of SPC information. The operation of one part of the process will not be affected by the nonoperation of another part of the process or control system. The fault tolerance of a modern DCS permits SPC data to be accumulated within a controller module for extended periods of time when an operations console is not available to display and archive this information, and permits historical SPC information to be maintained within the controller memory without electrical power.

AN APPROACH TO SPC USING ON-LINE TOOLS

The low-cost, incremental expansion capability of the DCS permits low-cost incremental implementation of on-line SPC tools. These on-line tools can provide the basis for either beginning an effective SPC program or enhancing the effectiveness of an existing SPC program.

On-line SPC tools can be implemented using the spare capacity of an existing DCS or they can be designed into a DCS replacement for an existing process unit control system. As SPC experience and effectiveness grows, on-line SPC tools can be easily implemented for additional process parameters, and additional features can be added to the DCS to further improve SPC effectiveness (e.g. data archiving and off-line analysis functions).

Incremental development of an SPC program using on-line SPC tools might follow this sequence:

1) Several DCS controllers are modified to provide an on-line control chart, SPC alarms and on-line Pareto analysis for the most critical process parameter of each major process unit.

2) After a sufficient process history has been accumulated for on-line calculation of reliable control limits (e.g. one time horizon), the cause for each incident of abnormal process variation is aggressively determined and entered into the on-line Pareto analysis. The relative cost impact for the on-line Pareto analysis is estimated for each cause as it is identified, and adjusted as necessary when new causes are identified.
3) After several incidents have been identified for several causes, the most costly 20% of the identified causes for abnormal process variation are aggressively eliminated or minimized.

4) Steps 2 and 3 are repeated until the normal process variation is roughly 2/3 of the manufacturing specification tolerance, or until no specific causes can be identified or quickly eliminated.

5) Process control setpoints are adjusted to shift the grand average closer to the most economical limit of the manufacturing specification without an on-line control limit crossing the specification limit.

6) The process economics are closely monitored to quantify the profitability impact of these process improvements.

7) Off-line cause/effect correlation is used to establish reliable relationships between easily obtained process measurements and difficult-to-measure process parameters.

8) Process control strategies are modified or developed to utilize easily obtained process measurements and the identified cause/effect relationships for indirect closed-loop control of the difficult to-measure process parameters.

9) Steps 2 through 8 are repeated, justifying additional effort by anticipated profitability improvements.

10) An off-line process capability study is accomplished with data from several time horizons (e.g. a year) to quantify natural process variation.

11) On-line control limits are managed toward the limits of natural process variation until the economic optimum is achieved (i.e. the costs of further improvements are balanced by the resulting increased profitability of operations).

Applying the Pareto Principle to an SPC program itself, it may be possible to achieve almost 80% of the benefit with only 20% of the effort. For many processes, this could mean that effective use of only the on-line SPC tools will be required to achieve substantial improvements in process profitability.
A DCS IMPLEMENTATION

This section discusses implementation of the on-line SPC tools in a Bailey NETWORK 90 microcomputer-based distributed control system. On-line SPC control charts are configured as dynamic trend displays in any of the Bailey CRT-based operations consoles -- the procedure used is the same as that for configuration of any process variable trend display. SPC alarms are configured into console graphic displays, just as any other process alarm. The on-line Pareto display is configured as a dynamic tabular display which accesses data from the controller module, just as any other NETWORK 90 on-line CRT display.

The computations and alarm processing for on-line SPC functions can be implemented in NETWORK 90 controllers using any of several programming languages, depending on the controller module selected:

- standard Bailey function blocks,
- interpreted BASIC,
- compiled C,
- BATCH 90 compiled batch configuration language.

Each language provides a unique combination of functionality and data processing efficiency.

For the purpose of illustration, the BASIC data processing for an on-line Shewhart Chart and the corresponding SPC alarms and Pareto Display will be presented. In this discussion, the critical process parameter is a laboratory test result which is entered periodically into the control system database by an operator through a CRT-based operations console.

Only minor modifications to this implementation are required to provide these on-line SPC tools for other types of process parameters (e.g. a continuous on-line process measurement, a periodic analyzer measurement, the error from a regulatory controller, etc.). For these applications, a subgroup of values can be established by periodically sampling the measurement or controller error over a specific period of time (e.g. a minute or an hour, depending on the process measurement).

The BASIC program to be discussed is shown in the APPENDIX. This BASIC program is executed within a Bailey controller module and communicates with the rest of the control system (i.e. measurement sensors, operations consoles) through standard Bailey function blocks, as shown in FIGURE 4, FIGURE 5 and FIGURE 6. This function block interface is presented schematically in the
form of logic diagrams which were generated by a Bailey
Engineering Work Station. A detailed discussion of these
function codes is provided by REFERENCE 8 and REFERENCE 9.

x-bar

X-BAR is the average value of X (arithmetic mean) for a
subgroup containing a specified number of values \(X_1, X_2 \ldots X_n\). The calculation of X-BAR is shown in Section 500 of the BASIC
program.

A Remote Manual Set Constant block (Function Code 68) in
FIGURE 4 permits the laboratory test value to be entered at the
operations console from a process graphic display or tabular
display. A transition of the Remote Control Memory block
(Function Code 62) from 0 to 1 designates that a new test value
is available for the calculations.

Each new value of X is passed through tunable limit checks
and the arithmetic mean is calculated by the BASIC program once n
values of X have been obtained. The subgroup size (n) may be
selected between 2 and 10 to align data collection with process
operations (e.g. n = 4 to provide two X-BAR values per shift for
a laboratory test result which is entered every hour). The value
of X-BAR is output from the program by a BASIC Real Output block
(Function Code 93) and captured for trending by the operations
console with a Trend block (Function Code 66).

x-bar-bar

X-BAR-BAR is the grand average of all X values within the
population of samples. It is calculated as an exponentially
weighted moving average of X-BAR for the past N subgroups in
Section 600 of the BASIC program, according to the following
equation:

\[
X\text{-BAR-BAR}_{\text{present}} = [X\text{-BAR-BAR}_{\text{past}} \times (1-K)] + [X\text{-BAR} \times K],
\]

where \(K = \frac{2}{(N+1)}\).

N is selected based on the desired time horizon to be used for
calculating the control limits (e.g. N = 168 for a 4-week time
horizon with 2 subgroups for each of 3 shifts per day).
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r and r-bar

R is the range of X values within each subgroup. R is calculated in Section 700 of the BASIC program from the values of X collected for each subgroup, according to the following equation:

\[ R = X_{\text{max}} - X_{\text{min}} \]

R BAR is calculated as the exponentially weighted moving average of R for the past N subgroups. This calculation is similar to the calculation of X-BAR-BAR and is shown in Section 800 of the BASIC program.

ucl(x) and lcl(x)

UCL(X) is the upper control limit for the process parameter (X) and represents the upper boundary of normal variation observed for the process parameter. LCL(X) is the lower control limit for the process parameter and represents the lower boundary of normal variation. The calculation of UCL(X) and LCL(X) is shown in Section 1100 of the BASIC program.

The control limits for X are calculated from the grand average of X values for the entire population of samples within the selected time horizon (X-BAR-BAR), and the average range (R-BAR) of values in the subgroups within the time horizon:

\[ \text{UCL}(X) = X\text{-BAR\-BAR} + (A2 \times R\text{-BAR}) \]
\[ \text{LCL}(X) = X\text{-BAR\-BAR} - (A2 \times R\text{-BAR}). \]

A2 is a statistical significance factor which is based on the number of data samples in each subgroup (n). As the number of data samples in each subgroup increases, the value of the statistical significance factor decreases and the control limit moves closer to X-BAR-BAR. This relationship reflects increased statistical confidence that abnormal variation will not fall within the calculated control limits. The value of A2 is taken from a data table stored within the BASIC program.

ucl(r)

UCL(R) is the upper control limit for R and represents the upper boundary for normal variation of the process parameter within a subgroup (short-term variation). UCL(R) is calculated
Section 1100 of the BASIC program, according to the following equation:

\[ \text{UCL}(R) = D4 \times \text{R-BAR}. \]

D4 is a statistical significance factor based on the number of data samples in each subgroup \((n)\) and is taken from a data table stored within the BASIC program.

**Control Limit Alarms**

The alarm processing for SPC control limit alarms is shown in Section 1100 of the BASIC program. The SPC control limit alarm levels are automatically set for each SPC parameter by the calculated control limit. The control limit alarm state is output to the operations console using a BASIC Binary Output block (Function Code 94) and a Digital Output block (Function Code 45).

**SPC Pattern Alarms**

The implementation of SPC pattern alarms enhances the utility of the on-line SPC control chart and the on-line SPC limit alarms. A pattern alarm alerts the operator when the last several values of an SPC parameter fall into one of the patterns shown in **FIGURE 2**. The implementation of SPC pattern tests for X-BAR and R is shown in lines 1500 through 2799 of the BASIC program. The alarm state and alarm pattern identification are output to the console through a BASIC Real Output Block (Function Code 94) and an Analog Output block (Function Code 30) on **FIGURE 4**.

An on-line SPC control chart could also be implemented for the process variable manipulated by a regulatory controller. In this case, the pattern tests would be modified to provide only the appropriate pattern alarms since X-BAR can be expected to oscillate tightly around the grand average and exhibit very narrow control limits due to the regulatory action of the process controller.

**Pareto Analysis**

The on-line Pareto analysis is accomplished by counting the number of abnormal variation incidents assigned to each of 10 potential causes by the operator. The function block logic shown in **FIGURE 5** counts the number of times that a cause identification number is entered using the Pareto Display (**FIGURE**
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3) at an operations console. Each time the cause for an incident is entered, the analysis in Section 3000 of the BASIC program is repeated.

The total number of entries for each cause is multiplied by an adjustable cost factor which is entered through a Manual Set Constant block (Function Code 2). This cost factor may represent either the absolute cost of abnormal variation attributed to a cause or the relative factor which scales the cost impact of one cause to the other potential causes. This cost factor can be adjusted at any time and the Pareto analysis will immediately reflect the adjustment.

The cost-weighted number of incidents for each potential cause is totaled and the contribution of each cause to this total is calculated as a percentage. Each potential cause is rank-ordered from highest to lowest based on its cost impact percentage. The cumulative percentage of abnormal variation accounted for by the list down through each potential cause (e.g. 80% for the second of ten potential causes) is then calculated.

The BASIC program also counts the total number of SPC alarms which have occurred. The percentage of these incidents of abnormal variation which has been assigned a cause by the operator is calculated from the total incident count.

The Pareto analysis information is output to the operations console through BASIC Real Output (Function Code 93) and Analog Output (Function Code 30) blocks. This information includes the percentage of all SPC alarms which has been assigned a cause, as well as the rank-ordered cause identification number and associated percentages for each potential cause.

Product/Grade Change Compensation

The logic required to accommodate different products and/or grades is shown in Section 300 of the BASIC program. The historical values for X-BAR-BAR, R, the incident count for each potential cause, and the total SPC alarms are stored as a function of a product/grade identification number. When the grade/product is changed by the operator from the operations console, the control limits, grand average and incident counts are changed immediately, but new values of X are excluded from the calculation of the grand average and control limits for a selected number of samples to allow time for the process to stabilize at the new production conditions. SPC alarms are also inhibited for the selected number of samples to prevent false alarms.
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The grade is entered by the operator from the operations console through a Remote Manual Set Constant block (Function Code 68) on FIGURE 4. This entry causes the Real Recipe Table blocks (Function Code 118) for X-BAR-BAR and R-BAR in FIGURE 4, and each potential cause incident count and total SPC alarms from FIGURE 6, to input the historical values for the selected grade into the BASIC program.

Fault Tolerance

This implementation has been designed to prevent loss of long-term data required for on-line SPC control charts and Pareto analysis when electrical power is disconnected from the controller module. Each time a subgroup or cause assignment is processed, the critical values are saved to nonvolatile memory so that only the data missed when the controller is out-of-service will be excluded from the SPC calculations. A redundant controller can be used to minimize the risk of lost data due to controller failure.

The Real Recipe blocks (Function Code 118) which are used for product/grade change compensation on FIGURE 4 and FIGURE 6 are also used for nonvolatile storage of the previous values of X-BAR-BAR, R-BAR incident counts for each potential cause, and the total number of SPC alarms. When power is applied to the controller module, the BASIC program reads the previous values from these Real Recipe blocks.

Expansion to Multiple Process Parameters

This implementation has also been designed for simple integration into an existing controller module and/or expansion to multiple process variables. The entire BASIC program and function block configuration can be inserted into a controller module using the cut-and-paste edition features of the Bailey Engineering Work Station.

The BASIC program can provide SPC data processing for any number of critical process parameters, as long as the controller has available memory. To increase the number of process parameters, ND must be changed from 1 to the desired number in Section 10000 of the BASIC program -- a data array will be formed by the BASIC program and the process parameters will be processed at roughly 2/second (the compiled C and BATCH 90 versions of this program execute four times faster). Additionally, the entire function block configuration shown in FIGURE 4, FIGURE 5 and FIGURE 6 must be duplicated for each process parameter and
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connected to the Basic program -- this can also be accomplished with the cut-and-paste editing features of the Bailey Engineering Work Station.

Each process variable with full implementation of on-line Shewhart Control Chart, SPC alarms and on-line Pareto analysis requires 2.6 kBytes of nonvolatile memory. Implementation without the on-line Pareto analysis requires 0.8 kBytes of nonvolatile memory. These requirements are more related to the function block input/output processing, than the BASIC program memory requirements. A NETWORK 90 controller with 80 kBytes of nonvolatile memory could support a maximum 30 process parameters with on-line Pareto Analysis or 100 parameters without on-line Pareto analysis. The presented SPC configuration can be expanded to utilize any available memory in existing DCS controllers for on-line SPC control charts and/or Pareto analysis.

CONCLUSION

The capabilities of modern distributed digital process control systems enhance and extend the utility of classical SQC techniques. On-line SPC tools can be effective operations tools. Operators can be quickly and automatically alerted to abnormal process variation without time consuming preparation and interpretation of manual SPC control charts. Operators can be quickly directed to the most costly potential causes for abnormal variation to minimize its overall cost impact on process operation. Most importantly, operators can search for the cause of abnormal variation while it is actually occurring -- this substantially increases the probability that a specific cause will be identified and eliminated. In the hands of process operators, these on-line SPC tools can produce substantial improvements in the profitability of process operations.

Further, the on-line SPC tools discussed in this paper can be easily and cost-effectively implemented within a modern process control system. They can often occupy unused controller memory and console display capacity. Using appropriate engineering tools, they can be integrated with process control functions with very little effort.
REFERENCES


FIGURE 2 - Typical SPC Pattern Tests

Test 1. Nine points in a row in Zone C or beyond

Test 2. Six points in a row steadily increasing or decreasing

Test 3. Fourteen points in a row alternating up and down

Test 4. Two out of three points in a row in Zone A or beyond

Test 5. Four out of five points in a row in Zone B or beyond

Test 6. Fifteen points in a row in Zone C (above and below centerline)

Test 7. Eight points in a row on both sides of centerline with none in Zones C
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FIGURE 3 - On-Line Pareto Display

ON-LINE PARETO ANALYSIS - H-FACTOR OVERSHOOT

<table>
<thead>
<tr>
<th>ABNORMAL VARIATION</th>
<th>ASSIGNED CAUSE</th>
<th>#5 DIGESTER BLOW COLLISION</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAUSE</td>
<td>NO</td>
<td>197</td>
</tr>
<tr>
<td>ASSIGNMENT</td>
<td>TOTAL ASSIGNED CAUSES</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>ASSIGNMENT RATE</td>
<td>81.12 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RANK</th>
<th>CODE</th>
<th>CAUSE DESCRIPTION</th>
<th>% OF TOTAL</th>
<th>CUM % OF TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>#2</td>
<td>HIGH BLOW TANK LEVEL</td>
<td>2.39</td>
<td>72.39</td>
</tr>
<tr>
<td>2</td>
<td>#4</td>
<td>WASHER DOWN</td>
<td>11.91</td>
<td>84.30</td>
</tr>
<tr>
<td>3</td>
<td>#5</td>
<td>DIGESTER BLOW COLLISION</td>
<td>7.28</td>
<td>92.29</td>
</tr>
<tr>
<td>4</td>
<td>#7</td>
<td>HIGH ACCUMULATOR LEVEL</td>
<td>3.50</td>
<td>95.79</td>
</tr>
<tr>
<td>5</td>
<td>#6</td>
<td>DIGESTER TRS COLLISION</td>
<td>1.49</td>
<td>97.29</td>
</tr>
<tr>
<td>6</td>
<td>#9</td>
<td>OPERATOR ERROR</td>
<td>0.84</td>
<td>98.13</td>
</tr>
<tr>
<td>7</td>
<td>#3</td>
<td>BLOW TANK INSTRUMENTATION MALFUNCTION</td>
<td>0.85</td>
<td>98.78</td>
</tr>
<tr>
<td>8</td>
<td>#8</td>
<td>DIGESTER INSTRUMENTATION MALFUNCTION</td>
<td>0.60</td>
<td>99.39</td>
</tr>
<tr>
<td>9</td>
<td>#1</td>
<td>PLUGGED BLOWLINE</td>
<td>0.46</td>
<td>99.85</td>
</tr>
<tr>
<td>10</td>
<td>#10</td>
<td>OTHER OR UNKNOWN</td>
<td>0.14</td>
<td>100.0</td>
</tr>
</tbody>
</table>

TOTAL ASSIGNED COST - 159.
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FIGURE 4 - Bailey NETWORK 90 Function Block Configuration for On-Line SPC Control Chart and SPC Alarms
FIGURE 5 - Bailey NETWORK 90 Function Block Configuration for On-Line Pareto Analysis
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FIGURE 6 - Bailey NETWORK 90 Function Block Configuration for On-Line Pareto Analysis Product/Grade Change Compensation
APPENDIX - BASIC Program for On-Line SPC Tools

0 REM ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
0 REM
0 REM
0 REM           STATISTICAL PROCESS CONTROL
0 REM
0 REM
0 REM           SPC PATTERN ALARMS
0 REM
0 REM
0 REM           PARETO ANALYSIS
0 REM
0 REM
0 REM ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
0 REM
0 REM
5 IF NOT INIT THEN GOSUB 10000 INITIALIZATION
10 ON ERROR GOTO 20000
15 FOR NV = 1 TO ND
20 GOSUB 200 N M INPUT
30 GOSUB 300 GRADE CHANGE
35 IF NOT NEVX(NV) THEN 130
40 GOSUB 400 X-INPUT
45 IF NOT IFLG(NV) THEN 130
50 GOSUB 500 XBAR CALC
60 GOSUB 600 XBARBAR CALC
70 GOSUB 700 R CALC
80 GOSUB 800 RBAR CALC
90 REM GOSUB 900 S CALC
100 REM GOSUB 1000 SBAR CALC
110 GOSUB 1100 CONTROL LIMIT CALC
120 IF IFLG(NV) THEN GOSUB 1400 PATTERN ANALYSIS
130 IF IPARETO(NV) THEN GOSUB 3000 PARETO ANALYSIS
140 GOSUB 4000 OUTPUT
150 NEXT NV
160 GOSUB 25000 END
0 REM
0 REM ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
0 REM
0 REM
200 HOUR-BIN(20) MIN=BIN(21)
205 NTST(NV)=BIN(1027+(NV 1)*15)
210 NEVX(NV)=NTST(NV) AND NOT OLDX(NV) OLDX(NV)= NTST(NV)
215 NSUB(NV)=FNMINT(1,FNAMAX(1,BIN(1031+(NV-1)*15))) LIMIT CHECKED
220 MSP(NV)=FNAMAX(1,BIN(1030+(NV-1)*15))
225 A2(NV)=CLA2(NSUB(NV)) REM A1(NV)=CLA1(NSUB(NV))
230 D4(NV)=CLD4(NSUB(NV)) REM B4(NV)=CLB4(NSUB(NV))
235 NEVGRD(NV)=B5(BIN(35+(NV 1)*25)
240 IF NEVGRD(NV) THEN GRADE(NV)=BIN(36+(NV 1)*25) JST(NV)=BIN(1032+(NV-1)*15)
245 IF GRADE(NV)=0,0,0,0,0 THEN NEVGRD(NV)=0
250 OLDGRD(NV)=GRADE(NV)
255 IF NOT IPARETO(NV) THEN RETURN
260 IRESET(NV)= BIN (1271+(NV-1)*25)

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APPENDIX (cont'd)

265 REM CAUSE(NV)=BIN(411+(NV-1)*4Q) REM NEWCAUSE(NV)=BIN(412+(NV-1)*4Q)
270 FOR I=1 TO 10 CSTFCTR(I,NV)=BIN(1250*I+(NV 1)*25) NEXT I
299 RETURN

0 REM
0 REM ———— —————————— GRADE CHANGE ———— —————————— ————
0 REM
300 IF NEWGRD(NV) THEN IGROD(NV)=1 GCNTR(NV)=0
305 IF NOT IGROD(NV) THEN RETURN
310 IF NEWX(NV) THEN GCNTR(NV)=GCNTR(NV)+1
315 IF GCNTR(NV)<=ITST(NV) THEN NEWX(NV)=0 ELSE IGROD(NV)=0
320 XBB(NV)=BIN(1035+(NV-1)*15) RB(NV)=BIN(1035+(NV-1)*15)
322 REM SB(NV)=BIN(1035+(NV-1)*15)
325 IF XBB(NV)=0 OR RB(NV)=0 THEN M(NV)=0 ELSE GOSUB 380
330 IF NOT IPARETO(NV) THEN 370
335 PCNTR(NV)=0 PT(NV)=0
340 FOR I=0 TO 2 ILIM(NV, I)=0 PATTERN(NV, I)=0 NEXT I
345 TCNTR(NV)=BIN(1272+(NV 1)*25)
350 FOR J=1 TO 10
355 CCNTR(J, NV)=BIN(1260+J*(NV-1)*25)
360 PCNTR(NV)=PCNTR(NV)+CCNTR(J, NV)
365 NEXT J
370 BOUT 1657+(NV-1)*20,-NEWGRD(NV)
379 RETURN
380 XBARBAR(NV)=XBB(NV)
385 RBAR(NV)=RB(NV)
390 REM SEAR(NV)=SB(NV)
395 M(NV)=MSMP(NV)
399 RETURN

0 REM
0 REM ———— ———————————— X-INPUT ———— ———————————— ————
0 REM
400 IFLG(NV)=C
410 INC1(NV)=INC1(NV)+1
420 X(INC1(NV), NV)=SAMPLE BIN(31+(NV-1)*25)
430 IF INC1(NV)<NSUB(NV) THEN RETURN
440 IFLG(NV)=1 INC1(NV)=0
499 RETURN

0 REM
0 REM ———— ———————————— XBAR ———— ———————————— ————
0 REM
500 M(NV)=M(NV)+1 MFILG(NV)=0
510 IF M(NV)<MSMP(NV) THEN M(NV)=MSMP(NV)
520 SUM = 0
530 FOR J=1 TO NNSUB(NV)
540 SUM=SUM+X(J, NV)
550 NEXT J
560 XBAR(NV)=SUM/NNSUB(NV)
599 RETURN
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APPENDIX (cont’d)

0 REM
0 REM
0 REM
0 REM

600  AK(NV)=2/(M NV)*)1
610  XBARBAR(NV)=XBARBAR(NV)*(1-AK(NV)+XBAR(NV)*AK(NV)
699  RETURN
0 REM
0 REM
0 REM
0 REM

700  XMAX=X(1,NV) XMIN=X(1,NV)
710  FOR I 1 TO NSUB(NV)
720    IF X(I,NV)>XMAX THEN XMAX=X(I,NV)
730    IF X(I,NV)<XMIN THEN XMIN=X(I,NV)
740    NEXT I
750  IF NSUB(NV)>1 THEN 790
760  IF XOLD(NV)>XMAX THEN XMAX=XOLD(NV)
770  IF XOLD(NV)<XMIN THEN XMIN=XOLD(NV)
780  XOLD(NV)=X(1,NV)
785  IF NOT PASS(1,NV) THEN PASS(1,NV)=1 RETURN
790  R(NV)=XMAX (MIN
799  RETURN
0 REM
0 REM
0 REM
0 REM

800  RBAR(NV)=RBAR(NV)*(1-AK(NV))+R(NV)*AK(NV)
899  RETURN
0 REM
0 REM
0 REM
0 REM

900  SX2=0
910  FOR J=1 TO NSUB(NV)
920    SX2=SX2+X(J,NV)*X(J,NV)
930    NEXT J
940  IF NSUB(NV)>1 THEN 980
950  SX2=X(1,NV)*X(1,NV)+XOLD(NV)*XOLD(NV)
955  AVG=(X(1,NV)+XOLD(NV))/2
960  XOLD(NV)=X(1,NV)
965  IF NOT PASS(2,NV) THEN PASS(2,NV)=1 RETURN
970  S(NV)=SQRT((SX2/2)-AVG*AVG)*2) RETURN
980  S(NV)=SQRT((SX2/NSUB(NV)))-XBAR(NV)*XBAR(NV)+(NSUB(NV)/(NSUB(NV)-1)))
999  RETURN
0 REM
0 REM
0 REM
0 REM

1000  SBAR(NV)=SBAR(NV)*(1-AK(NV)+S(NV)*AK(NV)
1099  RETURN
0 REM

30
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APPENDIX (cont’d)

0 REM ================= CONTROL LIMITS ==================
0 REM
1100 UCLX(NV)=XBARBAR(NV)+RBAR(NV)*A2(NV)
1105 LCLX(NV)=XBARBAR(NV)-RBAR(NV)*A2(NV)
1110 REM UCLX(NV)=XBARBAR(NV)+SBAR(NV)*A1(NV)
1115 REM LCLX(NV)=XBARBAR(NV)-SBAR(NV)*A1(NV)
1120 UCLR(NV)=RBAR(NV)*B4(NV)
1125 REM UCLS(NV)-SBAR(NV)*B4(NV)
1130 FOR I=0 TO 2 ILIM(NV,I)=O NEXT I
1135 IF XBAR(NV)>UCLX(NV) THEN ILIM(NV,0)=1
1140 IF XBAR(NV)<LCLX(NV) THEN ILIM(NV,1)=-1
1145 IF R(NV)>UCLR(NV) THEN ILIM(NV,2)=-1
1150 REM IF S(NV)>UCLS(NV) THEN ILIM(NV,2)=-1
1199 RETURN
0 REM
0 REM ================ UPDATE TREND FILE ===============
0 REM
1400 FULL=O IF PT(NV)<EOF THEN PT(NV)=PT(NV)+1 ELSE FULL=-1
1405 FOR MM=1 TO 2
1410 IF FULL THEN 1415 ELSE 1420
1415 FOR I=1 TO EOF 1 TREND(I,MM,NV)=TREND(I+1,MM,NV) NEXT I
1420 IF MM=1 THEN TREND(PT(NV),MM,NV)=XBAR(NV) GOTO 1500
1425 TREND(PT(NV),MM,NV)=R(NV)
0 REM
0 REM ============== TREND PATTERN ANALYSIS =========
0 REM
0 REM **** SET UP CONTROL CHART PARAMETERS
0 REM
1500 IF MM=1 THEN BAR=XBARBAR(NV) UCL=UCLX(NV) LCL=LCLX(NV) GOTO 1510
1505 BAR=RBAR(NV) UCL=UCLR(NV) LCL=0
1510 XOC=O PATTERN(NV,1)=O PATTERN(NV,2)=0 SIGMA=(UCL-BAR)/3
0 REM
0 REM **** CHK FCK TO ENABLE PATTERN ANALYSIS
0 REM
1515 ENABLE=-1
1520 IF (LCL<=UCL) OR (SIGMA<=0) OR (PT(NV)<5) THEN ENABLE=0
1525 BOUT 1651+MM+(NV-1)*20, -ENABLE: IF ENABLE THEN 1530 ELSE 1555
0 REM
0 REM **** TEST PATTERN RULES
0 REM
1530 FOR N=1 TO 7
1535 PO=FNAMAX(PT(NV)-RULE(N,2)+1,1)
1540 ON N GOSUB 2100,2200,2300,2400,2500,2600,2700
1545 IF XOC THEN PATTERN(NV,MM)=N: N=7
1550 NEXT N
1555 BOUT 1659+MM+(NV-1)*20, PATTERN(NV,MM)
1560 NEXT MM
1565 BOUT 1651+(NV-1)*20, -NTST(NV)
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APPENDIX (cont'd)

1570  GOSUB 25000
1599  RETURN
  O REM
  O REM **** RULE 1 SHIFT NINE POINTS IN A ROW ABOVE OR BELOW MEAN
  O REM
2100  ABOVE- 0 BELOW- 0
2110  FOR J = PO TO PT(NV)
2120  IF TREND(J,MM,NV) > BAR THEN ABOVE = ABOVE + 1
2130  IF TREND(J,MM,NV) < BAR THEN BELOW = BELOW + 1
2140  NEXT J
2150  IF FNMAX(ABOVE,BELOW) >= RULE(1,1) THEN XOC = 1
2199  RETURN
  O REM
  O REM **** RULE 2 TREND SIX POINTS IN A ROW INCREASING OR DECREASING
  O REM
2200  INC= 0 DEC= 0
2210  FOR J = PO TO PT(NV) - 1
2220  IF TREND(J+1,MM,NV) > TREND(J,MM,NV) THEN INC= INC + 1
2230  IF TREND(J+1,MM,NV) < TREND(J,MM,NV) THEN DEC= DEC + 1
2240  NEXT J
2250  IF FNMAX(INC,DEC) >= RULE(2,1) THEN XOC = 1
2299  RETURN
  O REM
  O REM **** RULE 3 ALTERNATION 14 PTS IN A ROW ALTERNATING UP AND DOWN
  O REM
2300  ALT= 0
2310  FOR J = PO TO PT(NV) 1
2320  IF TREND(J,MM,NV) > TREND(J+1,MM,NV) AND TREND(J,MM,NV) > TREND(J+1,MM,NV) THEN ALT = ALT + 1
2330  IF TREND(J,MM,NV) < TREND(J-1,MM,NV) AND TREND(J,MM,NV) < TREND(J+1,MM,NV) THEN ALT = ALT + 1
2340  NEXT J
2350  IF ALT >= RULE(3,1) 2 THEN XOC = 1
2399  RETURN
  O REM
  O REM **** RULE 4 ZONE A 2 OF 3 POINTS GREATER THAN + OR TWO SIGMA
  O REM
2400  UZA = 0 LZA = 0 UPRZONEA = BAR+2*SIGMA LWRZONEA = BAR-2*SIGMA
2410  FOR J = PO TO PT(NV)
2420  IF TREND(J,MM,NV) > UPRZONEA THEN UZA = UZA + 1
2430  IF TREND(J,MM,NV) < LWRZONEA THEN LZA = LZA + 1
2440  NEXT J
2450  IF FNMAX(UZA,LZA) >= RULE(4,1) THEN XOC = -1
2499  RETURN
  O REM
  O REM **** RULE 5 ZONE B 4 OF 5 POINTS GREATER THAN + OR ONE SIGMA
  O REM
2500  UZB = 0 LZB = 0 UPRZONEB = BAR+SIGMA LWRZONEB = BAR-SIGMA
2510  FOR J = PO TO PT(NV)
2520  IF TREND(J,MM,NV) > UPRZONEB THEN UZB = UZB + 1
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APPENDIX (cont’d)

2530 IF TREND(J,MM,NV)<LWRZONEB THEN LIZB=LIZB+1
2540 NEXT J
2550 IF FNAMAX(UIB,LZB)>=RULE(5,1) THEN XOC= 1
2599 RETURN

0 REM
0 REM **** RUL- 6 STRATIFICATION 15 PTS IN A ROW WITHIN +/- ONE SIGMA
0 REM
2600 ZONEC= 0
2610 FOR J = 0 TO "N"(NV)
2620 IF TREND(J,MM,NV)>LWRZONEB AND TREND(J,MM,NV)<UPRZONEB THEN ZONEC=ZONEC+1
2630 NEXT J
2640 IF ZONEC> RULE(6,1) THEN XOC= 1
2699 RETURN

0 REM
0 REM **** RULE 7 MIXTURE 8 PTS IN A ROW OUTSIDE OF + OR ONE SIGMA
0 REM
2700 MIX= 0
2710 FOR J = PO TO PT(NV)
2720 IF TREND(J,MM,NV)<LWRZONEB OR TREND(J,MM,NV)>UPRZONEB THEN MIX=MIX+1
2730 NEXT J
2740 IF MIX>=RULE(7,"") THEN XOC= 1
2799 RETURN

0 REM
0 REM =----------- --- PARETO ANALYSIS --- --- --- ---
0 REM
3000 IF IRESET(NV) THEN GOSUB 3100
3010 IF IFLAG(NV) THEN GOSUB 3200
3020 GOSUB 3300 GOSUB 3400
3099 RETURN

0 REM
0 REM **** RESET PARETO PARAMETERS
0 REM
3100 FOR I=1 TO 10
3110 CCNTR(I,NV)=0
3120 CST(I,NV)=0
3130 PCOST(I,NV)=0
3140 NEXT I
3150 PCCNTR(NV)=0
3160 TCNTR(NV)=0
3199 RETURN

0 REM
0 REM **** UPDATE ALARM COUNTER
0 REM
3200 ITCNTR(NV)=0
3210 IF (PATTERN(NV,1)>=5) THEN ITCNTR(NV)=-1
3220 IF (PATTERN(NV,2)>=5) THEN ITCNTR(NV)=-1
3230 IF (LIM(NV,0) OR LIM(NV,1) OR LIM(NV,2)) THEN ITCNTR(NV)=-1
3240 IF ITCNTR(NV) THEN TCNTR(NV)=TCNTR(NV)+1
3299 RETURN
0 REM
0 REM **** UPDATE PARETO PARAMETERS
0 REM
3300 IF NOT NEWCAUSE(NV) THEN 3315
3305 CCNTR(CAUSE(NV),NV)=CCNTR(CAUSE(NV),NV)+1
3310 PCNTR(NV)=PCNTR(NV)+1
3315 FOR I=1 TO 10
3320 COST(I,NV)=CCNTR(I,NV)*CSTFCTR(I,NV)
3325 NEXT I
3330 TCOST(NV)=0
3335 FOR I=1 TO 10
3340 TCOST(NV)=TCOST(NV)+COST(I,NV)
3345 NEXT I
3350 FOR I=1 TO 10
3355 PCOST(I,NV)=COST(I,NV)/FNAMAX(1,TCOST(NV))
3360 NEXT I
3399 RETURN
0 REM
0 REM **** SORT PARETO PARAMETERS
0 REM
3400 FOR I=1 TO 10
3405 SRTCS(I,0)=I SRTCS(I,1)=100*PCOST(I,NV)
3410 NEXT I
3415 FOR J=2 TO 10
3420 JFGL=0
3425 FOR J=1 TO I-1
3430 IF JFGL THEN GOTO 3440
3435 IF SRTCS(I,1)>SRTCS(J,1) THEN JFGL=1 GOSUB 3500
3440 NEXT J
3445 NEXT I
3450 SUM=0
3455 FOR I=1 TO 10
3460 SRTCS(I,2)=SRTCS(I,1)*SUM
3465 SUM=SRTCS(I,2)
3470 NEXT I
3499 RETURN
0 REM
0 REM **** SWAP ARRAYS
0 REM
3500 TMP(0)=SRTCS(I,0) TMP(1)=SRTCS(I,1)
3510 FOR K=1 TO J STEP -1
3520 SRTCS(K,0)=SRTCS(K 0)
3530 SRTCS(K,1)=SRTCS(K-1,1)
3540 NEXT K
3550 SRTCS(J,0)=TMP(0) SRTCS(J,1)=TMP(1)
3599 RETURN
0 REM
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APPENDIX (cont'd)

0 REM ============= ------- OUTPUT ========= = ======= = == = == =============
0 REM

4000 BOUT 1663+((NV-1)*20, XBAR(NV)) BOUT 1664+((NV 1)*20, XBARBAR(NV))
4005 BOUT 1665+((NV-1)*20, UCLX(NV)) BOUT 1666+((NV-1)*20, LCLX(NV))
4010 BOUT 1667+((NV 1)*20, R(NV)) BOUT 1668+((NV-1)*20, RBAR(NV))
4015 BOUT 1669+((NV-1)*20, UCLR(NV))
4020 REM BOUT 1667+((NV-1)*20, S(NV)) REM BOUT 1668+((NV 1)*20, SBAR(NV))
4025 REM BOUT 1669+((NV-1)*20, UCLS(NV))
4030 BOUT 1658+((NV-1)*20, IFLG(NV)) BOUT 1659+((NV-1)*20, GRADE(NV))
4035 FOR I=0 TO 2 BOUT 1654+I+((NV-1)*20, -ILIM(NV, I)) NEXT I
4040 IFLG(NV)=0
4045 IF NOT Ipareto(NV) THEN RETURN
4050 BOUT 1701+((NV 1)*60, TCNTR(NV))
4055 BOUT 1702+((NV-1)*60, PCNTR(NV))
4060 BOUT 1703+((NV 1)*60, 100*PCNTR(NV)/FNAMAX(1, TCNTR(NV)))
4065 BOUT 1704+((NV-1)*60, TCOST(NV))
4070 FOR I=1 TO 10
4075 BOUT 1709+3*(I-1)+((NV-1)*60, SRTCT(I, 0))
4080 BOUT 1710+3*(I-1)+((NV-1)*60, SRTCT(I, 1))
4085 BOUT 1711+3*(I-1)+((NV-1)*60, SRTCT(I, 2))
4090 BOUT 1741+(I-1)+((NV-1)*60, CCNTR(I, NV))
4095 NEXT I
4098 BOUT 1705+((NV 1)*60, NEWCAUSE(NV)). BOUT 1706+((NV-1)*60, -ITCNTR(NV))
4099 RETURN
0 REM
0 REM ============= === PROGRAM INITIALIZATION =========== ======
0 REM
10000 OPEN #0, B, 1, H, N OPEN #1, B, 1, N, H, N
10005 A$= ###- BS= ###- CS= ###-###-
10100 DEFINT I-K, M, N DEFENG A-H, L, O-Z
10190 ND1 NUMBER OF PROCESS PARAMETERS
10200 DIM A1(ND), A2(ND), B4(ND), D4(ND)
10205 DIM C1A(10), C2A(10), C3A(10), C4A(10)
10210 DIM AK(ND), CAUSE(ND), CCNTR(10, ND), CCOST(10, ND), CSTFR(R, ND)
10215 DIM GCNTR(ND), GRADE(ND), IFLG(ND), ILIM(ND, 2), INCI(ND)
10220 DIM IPARETO(ND), IRESET(ND), ITCNTR(ND), IIST(ND), N(ND), MFLG(ND)
10225 DIM MNP(ND), MFLG(ND), MCAUSE(ND), MWGRD(ND), NSUB(ND)
10230 DIM NTST(ND), OLDGRD(ND), OLDM(ND), PATERN(ND, 2), PASS(2, ND)
10235 DIM PCNTR(ND), PT(ND), R(ND), RB(ND), RBAR(ND), RULE(7, 2)
10240 DIM SRTCT(10, 2), TCNTR(ND), TMP(1), TREND(20, 2, ND)
10245 DIM X(ND), XBAR(ND), XBARBAR(ND), XBB(ND), XOLD(ND)
10250 REM DIM S(ND), SBAR(ND), SB(ND)
10300 DEF FNAMAX(A, B)= -(B>A)*B-(A>B)*A
10310 DEF FNAMIN(A, B)= -(B<A)*B-(A<B)*A
0 REM
0 REM **** SET UP TREND PATTERN ANALYSIS RULES
0 REM
10500 DATA 9, 6, 14, 2, 4, 15, 8. REM NUMBER OF SUBGROUP INCIDENTS
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APPENDIX (cont'd)

10510 DATA 9.6,14.3,5,15.8 REM NUMBER OF SUBGROUPS TO BE EXAMINED
10520 FOR N = 1 TO 2
10530 FOR I = 1 TO 7 READ RULE(I,N) EOTF= FNNMAX(RULE(I,N),EOTF) NEXT I
10540 NEXT N
0 REM
0 REM ****** DEFINE STATISTICAL SIGNIFICANCE FACTORS
0 REM
10600 DATA 3 76,3 76,2 39,1 88,1 60,1 41,1 28,1 17,1 09,1 03 REM A1
10610 DATA 2 66,1 88,1 02,0 73,0 58,0 48,0 42,0 37,0 34,0 31 REM A2
10620 DATA 3 27,3 27,2 57,2 27,2 09,1 97,1 88,1 81,1 76,1 72 REM B4
10630 DATA 3 27,3 27,2 57,2 28,2 11,2 00,1 92,1 86,1 82,1 78 REM D4
10640 FOR I=1 TO 10 READ CLA1(I) NEXT I
10650 FOR I=1 TO 10 READ CLA2(I) NEXT I
10660 FOR I=1 TO 10 READ CLB4(I) NEXT I
10670 FOR I=1 TO 10 READ CLD4(I) NEXT I
0 REM
0 REM ****** READ AND CHECK HISTORICAL DATA
0 REM
10700 FOR I=1 TO ND
10710 GRADE(I)=BIN(36*(I 1)*25)
10720 XBB(I)=BIN(1034+(I-1)*15) RB(I)=BIN(1035+(I 1)*15)
10730 IF XBB(I)=0 OR RB(I)=0 THEN M(I)=0 GOTO 10750
10740 XBARBAR(I)=XBB(I) RBAR(I)=RB(I) M(I)=9999
10750 NEXT I
0 REM
0 REM ****** PARETO ANALYSIS ENABLE/DISABLE
0 REM
10800 DATA 1 REM 1 = ENABLE, 0 = DISABLE
10810 FOR I=1 TO ND READ IPARETO(I) NEXT I
10820 FOR I=1 TO ND
10830 IF NOT IPARETO(I) THEN 10890
10840 TNCNT(I)=BIN (1272+(I-1)*25)
10850 FOR J=1 TO 10
10860 CCNTR(J,I)=BIN (1260+J*(I-1)*25)
10870 PNCNT(I)=PNCNT(I)+CCNTR(J,I)
10880 NEXT J
10890 NEXT I
10900 INIT= -1
10999 RETURN
0 REM
0 REM =================================================================================
0 REM 0 REM
20000 ERNO= ERR ERRNL= ERL ON ERROR GOTO 0
20500 BOUT 1631, ERNO BOUT 1632, ERLN BOUT 1633, HOUR*100+MIN
20999 ERROR 199
0 REM

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APPENDIX (cont'd)

0 REM ========= = USER BREAK ========= =

0 REM
25000 IF INQUE=0 THEN RETURN ELSE ON ERROR GOTO 0
25500 IN ZZZ IF ZZZ=26 THEN OPEN #0,B,1,M,N ERROR 255
25999 IF INQUE=0 THEN 25500 ELSE RETURN

0 REM
0 REM ================= END OF PROGRAM ==============

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