A SIMULATION OF
SELECTED STATISTICAL PROCESS CONTROL METHODS

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the requirements for the degree of
Master in Technology
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ABSTRACT

A simulation program, SQC, was developed at the Production Technology Department, Massey University. The program was written in Vax Basic 3.0 which is structured programming language and is run on the Vax computer under the VAX/VMS operating system 4.5. SQC is a menu-driven program which was designed to simulate data from a variety of production processes subject to inherent random variation and predetermined changes; sample selection for statistical quality purposes. Such decisions were made via the available feature to allow for user interactive control of the process parameters and sample selection methods while the chart of selected method was plotted on the terminal screen as well as optionally on the printer.

The exercise has been done to test and to observe how the program performed and produced the output on the screen and terminal-format files. Moreover, the program evaluation was carried out by comparing with a published article, which is satisfactorily acceptable.

The SQC can be utilized as a teaching tool for students in practising how each statistical process control method performs and how to make a right decision at a right time and as a research tool to observe and use the simulated results to predict and to improve the production process in the future.

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CHAPTER 1

INTRODUCTION

Blum and Bingham (1979) said that computer simulation is the method used to determine 'what would happen if' in the system. By the definition, 'simulation is the process of designing a computerized model of a system (or process) and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies for the operation of the system' (Shannon,1975). It is an appropriate method of system study where an analytical approach is not practical. Nowadays, computer simulation is widely used in many applications, because computers provide the capability of testing the model repeatedly with a variety of different conditions suitable to the questions to be answered (Blum and Bingham, 1979). The results from the simulation enable the researchers to understand the performance of the present system and predict the performance in the future under various conditions.

The use of simulation applied to industrial area has been increasing rapidly in recent years. It has became an effective tool in problem solving and decision making for management because it can help imitate the production operation by varying the physical conditions to see what would happen under many different management strategies (Rao and Smith, 1974). Cousins et al. (1975) also described how simulation can be applied in quality control with a case study in manufacturing. They concluded that simulation offers an excellent method for decision making without interfering with day-to-day operations.

There are many statistical quality control researches that have been done by using simulation approach both on quality control techniques and management as Hahn (1985) suggested that statistics can help improve the quality of manufactured product. The quality simulation can clarify the techniques used to achieve a given quality goal in advance in various stages of product development (Osamu,1983).

However, sometimes, statistics is hard to understand by supervisors or operators without being trained. Therefore, education and training are an essential part of quality improvement (Juran, 1979). Gupta et al. (1987) said that education and training of entire workforce become a top priority in statistical process control scheme.

Computer laboratory in quality control using simulation method can be a good tool in training with many benefits (Bommer and Frazer, 1976).

- It provides decision making experience in constructing and applying decision rules to actual data.
- The experience provides the trainee with opportunity to experiment with alternative decision strategies.
- The process identifies faulty decision strategy allowing the trainee to analyze and benefit from errors.
- The trainee's confidence in utilizing quality control concepts is reinforced when he succeeds in developing an effective decision strategy.

Furthermore, Juran (1979) added that although the preparation of the simulation program for training is costly because of requiring considerable time by skilled analysts and programmers, once it is prepared it permits a good deal of flexibility in training and helps minimize total costs since it does not disturb the actual operation. Also the program provides the capability of testing and demonstrating the trials repeatedly with various questioned conditions.

The objectives of the study

1. To build a programming package that adequately simulates :-
   - data from a variety of production processes subject to inherent random variation and predetermined or random parameter changes.
   - sample selection for SQC purposes

2. To compare the performance of each control methods resulted from the simulation.

3. To utilize the package as a study tool both in research and laboratory practice for statistical quality control students.

Chapter 2 describes the statistical process control method only those provided in the established program and discussed the advantages and disvantages of each control method.

Chapter 3 explains the design and description of the program which is called SQC while Appendix 2 and 3 provide the diagram of program structure input specifications.

Chapter 4 provides the guidelines of how to run SQC and also demonstrated some examples to help users understand the use of SQC with both arbitrary data and data taken from some previous researches. In addition, Appendix 1, and 4 to 8 provide some useful informations of program maintenance for those users who are interested in program modification and development (see DEC, 1986a, 1986b and 1986c for more detail informations).

Chapter 5 concludes with the results of the study and suggests some interesting ideas for further study and program development.

CHAPTER 2

STATISTICAL PROCESS CONTROL

Many authors have described 'statistical process control' as the method used to determine the performance and to control variability of the process if it is performing naturally and to effectively detect the occurence of assignable causes in the process so that the appropriate remedial action can be taken in time. According to Squires (1987), process variability is an effect of the natural phenomenon of variability. There are two kinds of variability that may occur in a process :-

a) Random causes of variation is the inherent variation in a process due to a large number of small independent effects which are usually normally distributed and vary in an acceptable level.

b) Assignable causes of variation is the variation that is 'findable' (Bicking and Gryna, 1979). They arise from three sources : improperly adjusted machines, operators errors and/or defective raw materials (Montgomery, 1985).

Therefore, control charts have been designed as a tool used to eliminate those assignable causes and to produce uniform product.

Shewhart (1939) inidicated that there are three senses in which statistical control may play an important role in attaining uniformity in the quality of a manufactured product.

a) as a concept of a statistical state constituting a limit which is aimed to achieve the goal of improving process uniformity

b) as a technique of attaining uniformity

c) as a judgement.

Control Chart Methods

2.1 Pre-control

Pre-control was first developed in 1954 by a group of consultants and their client in an attempt to find a substitute for $\bar{X}$-R charts (Traver, 1985). Satterthwaite (1973) and Traver (1985) indicated that Pre-control can be a good alternative to the classical control chart where such a control chart is impractical, for example on short runs, the manufacturing process is often completed before the control limits are calculated. In some applications, the operators do not have time to record, calculate and plot the chart, which causes the loss or limiting of control of quality. Pre-control can help the operator setting up the process to the target because the $\bar{X}$-R control chart is not concerned with specification limits. While the control chart shows the process is statistically in control, the product is possibly not well targetted. However, Traver (1985) suggested that Pre-control should be used only when the process capability is safely less than the specifications while Montgomery (1985) proposed that the process capability ratio should be at least 1.15 and the percent of non-conforming is between 1 to 3%.

The concept of Pre-control is shown in figure 2.1. It is supposed that the quality characteristics is normally distributed and the specification limits are the same as the tolerance limits ($\mu \pm 3\sigma$). The process target is exactly half way between the lower (lsl) and upper (usl) specification limits and the lower (lpcl) and upper (upcl) pre-control lines are half way between target and specification limits.

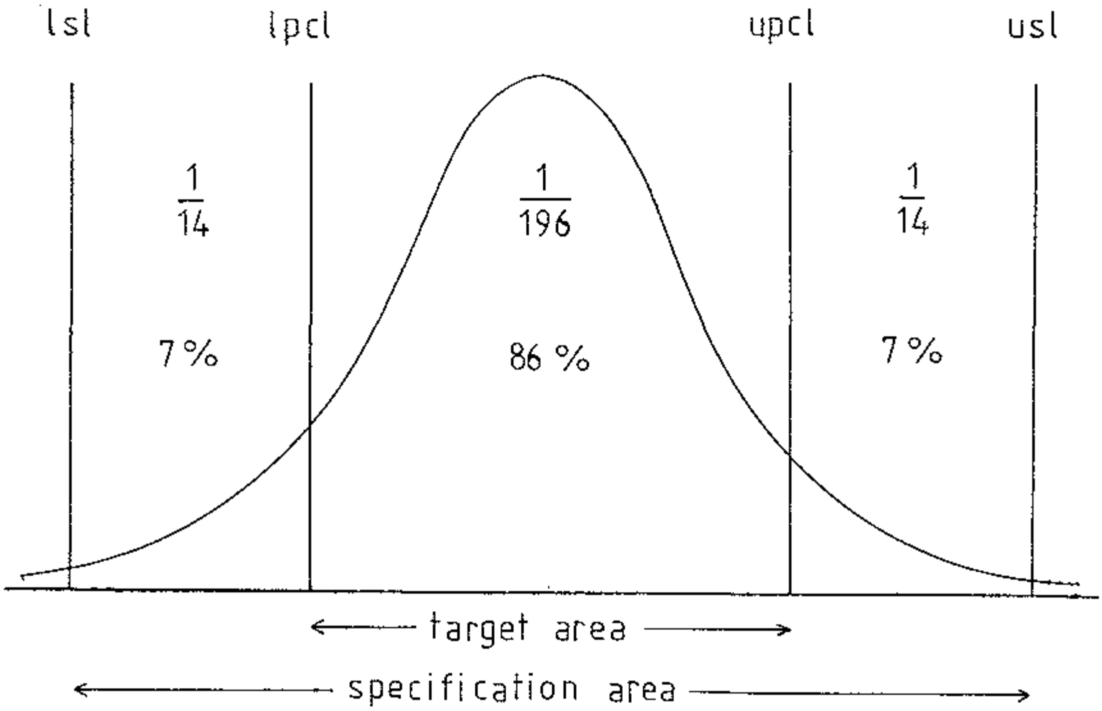

Figure 2.1 The location of Pre-control limits (Traver, 1985)

Since the process has normal distribution, there is 86% approximately chance the output item will lie within the target area and about 7% or 1/14 falling outside this area. Hence the probability that two items will be found consecutively outside the pre-control limits is only 1/14x1/14 = 1/196. When such event happens, it is likely that the process has shifted to out-of-control state (Montgomery, 1985). In case the process capability ratio is less than 1, the chance of this happenning is much less. As discussed above, the recommendation of Montgomery (1985) and Traver (1985) was based on this criteria.

The fundamental idea of the rules proposed Traver(1985) are :

a) Setup : job is okay when five items in a row are produced within target area.

b) Running : sample two consecutive items

- o If first item is within target, run (no need to measure the second item).
- o If the first item is not within target (but within specification limits), check the second item.
- o If the second item is within target, continue to run.
- o If both items are out of target, then adjust or correct process, go back to setup and follow rule 1.

Pre-control procedure in detail used in this study followed the standard rules described by Montgomery (1985).

Satterthwaite (1973) has pointed out the advantages of this method precisely as follows :

- Pre-control is practical. It is easy to train the supervisors and operators to use in a short time.
- Pre-control requires no record or plotting of data.
- Pre-control guarantees correct tolerances, process setup, process adjustment, good equipment maintemance, minimum inspection, minimum scrap, minimum work, and quality inspection and reliability.
- Pre-control measures process capability.

- Pre-control allows simple measurement methods and go/no-go gaging.

- Pre-control is statistical control, guarantees statistical distributions.

- Pre-control is a cost reduction method.

2.2 Shewhart Control Charts

In 1924, the control chart concepts were developed by Walter A. Shewhart of Bell Telephone Laboratories (Montgomery, 1985). Since then the control chart methods have been widely used in many applications.

Juran and Gryna (1980) have given the definition of a control chart that 'A control chart is a graphic comparison of process performance data to computed 'control limits' drawn as limit lines on the chart'. The process performance data are collected from groups of measured sampled products (subgroups) every regular interval of time.

The control chart is used to :

i) identify the inherent variation of the process
ii) detect the presence of assignable causes of variation
iii) sometimes perform a test of significance against the specifications
iv) judge whether the objectives have been achieved.

Process performance data mentioned above are measured either as :

i) Variable measurement - the product is measured on a continuous scale such as dimension, weight or volume etc.

ii) Attribute measurement - the product is measured on the basis of go/no-go inspection by the terms conforming/non-conforming or defective/non-defective or the number of defects or non-conformances found is recorded.

2.2.1 $\bar{X}$-R Chart is the chart for variables. $\bar{X}$ Chart is used to control the process average and the R chart measures the process variability.

Establishing the $\bar{X}$-R chart

i) A group of items are taken as a sample (so-called subgroup) every regular interval.

ii) The average ($\bar{X}$) and the range (R) are calculated for each sample.

iii) The number of samples taken are at least 20 or 25 which is recommended by many researchers (e.g. Knowler *et al.*, 1969; Hillier, 1969; Murdoch, 1979 and Montgomery, 1985).

iv) After the appropriate number of samples are taken during setup phase, the mean of sample averages is calculated denoted by $\bar{\bar{X}}$.

v) Calculate the average control chart limits by

$$\bar{\bar{X}} \pm 3\sigma_{\bar{x}}$$
$$= \bar{\bar{X}} \pm 3\frac{\sigma}{\sqrt{n}}$$

where $\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$

= population standard error

If σ is not known, it can be estimated by

$$\hat{\sigma}_x = \frac{\bar{R}}{d_2}$$

where $\bar{R}$ = average of ranges

d_2 = factors for central lines for range chart

The control limits then become

$$\bar{\bar{X}} \pm 3\frac{\bar{R}}{d_2\sqrt{n}}$$

$$\bar{\bar{X}} \pm A_2\bar{R}$$

where A_2 = factor for control limits for average chart

Then calculate the range control limits by

$$\text{lower limit} = \bar{R}\cdot D_3$$

$$\text{upper limit} = \bar{R}\cdot D_4$$

where D_3, D_4 = factors for control limits for range chart

Note : d_2, A_2, D_3, D_4 are parameters adopted from 'Factors for Constructing Variables Control Chart' (Montgomery, 1985).

After an $\bar{X}$-Chart and an R chart are already setup, if there are any subgroups or samples falling outside average control limits, it means that the process average has shifted. Similarly, if there are any subgroups or samples falling outside the range control limits, it shows that the process variability is out of control. Then the process would be checked to find out the assignable causes and the appropriate action should be taken.

2.2.2 P Chart is a control chart for attributes. The concept is concentrated on fraction non-conforming items produced by the process. The term 'fraction non-conforming (p)' is defined as the ratio of the number of non-conforming items in a contain population (D) to the total number of items in that population (N) which is based on the binomial distribution, i.e.

$$\hat{p} = \frac{D}{N}$$

then the mean and standard deviation of $\hat{p}$ are

$$\mu_{\hat{p}} = p$$

$$\sigma_{\hat{p}} = \sqrt{\frac{p(1-p)}{n}}$$

where n = sample size

The control chart limits for p are defined as :

$$\bar{p} \pm 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$$

where $\bar{p}$ = average of individual sample non-conforming

Montgomery (1985) mentioned that, in practice, a standard value of p will be given as a target value for the process fraction of nonconforming. If the fraction samples indicate the out-of-control process, the manufacturer must determine whether the process is out of control at the target p but in control at some other value of p.

2.2.3 C Chart (Chart of non-conformities or defects) is also a control chart for attributes. Sometimes, a non-conforming unit of product does not meet one or more specifications for that product. Each part for which a specification is not achieved is called a defect or non-conformity (Montgomery, 1985). Therefore, a non-conforming product has at least one defect. However, the severity of the defects depends on product's nature or usage, it is likely that an item that has some defects might not be classified as non-conforming product. In real situation, the chance of occurring of non-conformities is random or, in other words Poisson distributed, with mean and standard deviation c and $\sqrt{c}$, respectively.

Then the 3-sigma control chart limits for non-conformities are :

$$c \pm 3\sqrt{c}$$

if standard deviation is not known, $\sigma_{\bar{c}}$ can be estimated by $\sqrt{c}$ and the limits become

$$\bar{c} \pm 3\sqrt{\bar{c}}$$

where $\bar{c}$ = average number of defects

The C chart is used where the number of defects is obtained on one unit inspection.

2.2.4 U Chart (Chart of non-conformities per unit)

The concept of this chart is the same as c-chart but the number of defects is observed on unit inspections of units, n when n>1. Therefore, the 3-sigma control limits of non-conformities per unit are obtained by

$$\bar{u} \pm 3\sqrt{\frac{\bar{u}}{n}}$$

where $\bar{u}$ = average number of defects per unit inspection

2.3 Cumulative Sum Chart (CuSum Chart)

CuSum chart was first developed by E. S. Page and has been studied by many researchers (Montgomery, 1985). Page considered the problem of detecting a change in the parameter of the distribution of the quality characteristic using average run length (ARL) to develop rules that use all the past observation since the action was last taken, where the process inspection schemes were developed to detect variation in the parameter in one or two directions (Gibra, 1975). Actually, a change of process mean in the conventional control chart is a change of slope in the CuSum, where the slope is calculated from :

$$\text{slope} = \frac{\text{a change in CuSum observed}}{\text{number of samples between observed CuSums}}$$

CuSum chart can be applied to either variable controls or attribute control (Murdoch, 1979; Montgomery, 1985). If a sequence of samples x_1, x_2,.... is being produced then the CuSum values are developed as follows :

$$\begin{aligned}
S_1 &= x_1 - k \\
S_2 &= S_1 + (x_2-k) = (x_1-k)+(x_2-k) \\
S_3 &= S_2 + (x_3-k) = (x_1-k)+(x_2-k)+(x_3-k) \\
&\vdots \\
S_r &= S_{r-1} + (x_r-k) = \sum_{i=1}^{r} (x_i-k) \qquad \text{......(2.1)}
\end{aligned}$$

where k is the reference value. Practically it is usually set to the process average of the control chart.

If the process remains in control around the target value, say μ_0, the cumulative sum should vary randomly about zero. If the mean shifts either upward, causing positve CuSum value, or downward, causing negative CuSum value, it means that the process has shifted and action should be taken to find out what are the assignable causes.

The cumulative sum chart is the plotting of cumulative sum described by equation (2.1) against the number of samples taken.

There are a few methods that use to detect the shift of the process in CuSum chart. The method used in this study is called modified CuSum which is adopted from the British Standards (British Standards Institution, 1980).

Calculation algorithm for modified CuSum

Let σ_e = population standard error

m = number of samples at setup phase

T = reference value (= process average)

K^+ = upper reference value = $T + (0.5\sigma_e)$

K^- = lower reference value = $T - (0.5\sigma_e)$

$+h$ = upper decision line = $5\sigma_e$

$-h$ = lower decision line = $-5\sigma_e$

S_i^+ = cumulative upper CuSum at i^{th} sample

D_i^+ = $x_i - K^+$

S_i^- = cumulative lower CuSum at i^{th} sample

D_i^- = $x_i - K^-$

a) Upper CuSum

1) set counter $i = 1$
2) if $i = 1$ then $S_1^+ = \max(0, D_1^+)$
   otherwise $S_i^+ = \max(0, S_{i-1}^+ + D_i^+)$
3) $i \leftarrow i+1$
4) if $i > m$ then stop
   otherwise goto 2

b) Lower CuSum

1) set counter $i = 1$
2) if $i = 1$ then $S_1^- = \min(0, D_1^-)$
   otherwise $S_i^- = \min(0, S_{i-1}^- + D_i^-)$
3) $i \leftarrow i+1$
4) if $i > m$ then stop
   otherwise goto 2

If either upper or lower decision line is touched or crossed, the signal is generated that the process mean has shifted.

Advantages and disadvantages of each method

o $\bar{X}$-R chart :

Advantages

1. Measured data obtained provide detail information on process average and variation which can be used in troubleshooting when required.

2. Can use small sample size.

Disadvantages

1. Major disadvantage is that it only uses the information about the process contained in the last plotted point and ignored the information in the sequence points (Montgomery et al., 1987).

2. Does not concern with specification limits, sometimes can be confused.

3. Cannot be used with go/no-go type of data.

4. It is not understood without being trained.

o P chart :

Advantages

1. Data required are often already available from inspection record. Only available method if datais binomial.

2. Easily understood by personnel.

3. Provide overall picture of quality.

4. Can be used where data is not easily measured.

Disadvantages

1. Does not provide detailed information of individual characteristics.

2. Does not recognize different degree of effectiveness in units of product.

3. Requires a large sample.

- C and U chart :

Advantages

1. It is only available method if data is Poisson.

2. The same as P chart, but also provide a measure of defectiveness.

Disadvantages

1. Does not provide detailed information of individual characteristics.

2. Does not recognize different degree of effectiveness in units of product.

o CuSum chart :

Advantages

1. It is more effective than Shewhart control chart in detecting small shifts in process average (Murdoch,1979; Page, 1961) on the order of $0.5\sigma_{\bar{x}}$ to ~ $2\sigma_{\bar{x}}$ according to Montgomery(1985).

2. It is more general than Shewhart charts in that control can be achieved by individual readings (i.e. sample size n = 1).

3. Process shift is easily detected visually by the change in slope of the plot.

Disadvantage

Lucas(1973) noted that for large process shifts, detection by CuSum can be very slow. Therefore, he proposed V-mask method to detect large process shifts. However, Ewan(1963) mentioned about the importance of scale used for V-mask and Cusum chart therefore he advised to use a constant ratio of vertical scale in the units of sample standard error to that of plotting interval.

CHAPTER 3

SQC PROGRAM DESCRIPTION

This chapter describes the details of the design of the SQC program and the various techniques used in this study.

One of the important features provided are selective menus for users' decision making. There are two kinds of menu provided in the program performing different functions :

- o Prompt menu : is the menu that informs the user what kind of input is required by the program next and is ready to accept that input.

- o Display menu : is the list of useful information to supply the user to know what has been going on at that stage including message responses and error responses. The first type is the information from the program that gives some warnings to the user whenever input is incorrectly entered but is not serious. (See detail in section 6, Chapter 4). In this case, that incorrect value will be either reset to system's default or re-entered by the users. The later is message to inform the user that the entered input is absolutely invalid and not accepted by the program and the reentering will be requested.

3.1 Program Overview

SQC was developed at the Production Technology Department, Massey University. The program was written in Vax Basic 3.0 (DEC, 1986a, 1986b) which is a structured programming language. SQC is run on the Vax computer under the VAX/VMS operating system version 4.5 with the VT220-compatible terminal. The graphic phase in the program is supported by Vax Basic 3.0 based on Vax GKS 2.0 (DEC, 1987c)

SQC is a menu-driven program which allows users to interact and make decisions via the menu provided. In addition, SQC is not command language orientated and hence 'on-line help menu' facility and some other flexibility are not provided for users. However, the menu responses and display menu have been designed to help the user wherever possible.

Users of this SQC program are supposed to have some basic knowledge in statistics to be able to understand and determine the results provided by the program. The model structure is shown in Figure 3.1.

3.2 Purposes of the Program Usage

3.2.1 SQC used as a research tool for investigation and evaluation of the effectiveness of different statistical control procedures in different situations.

3.2.2 SQC used as a teaching tool for students to practise and to observe the performance of various SQC control charts when parameters are varied.

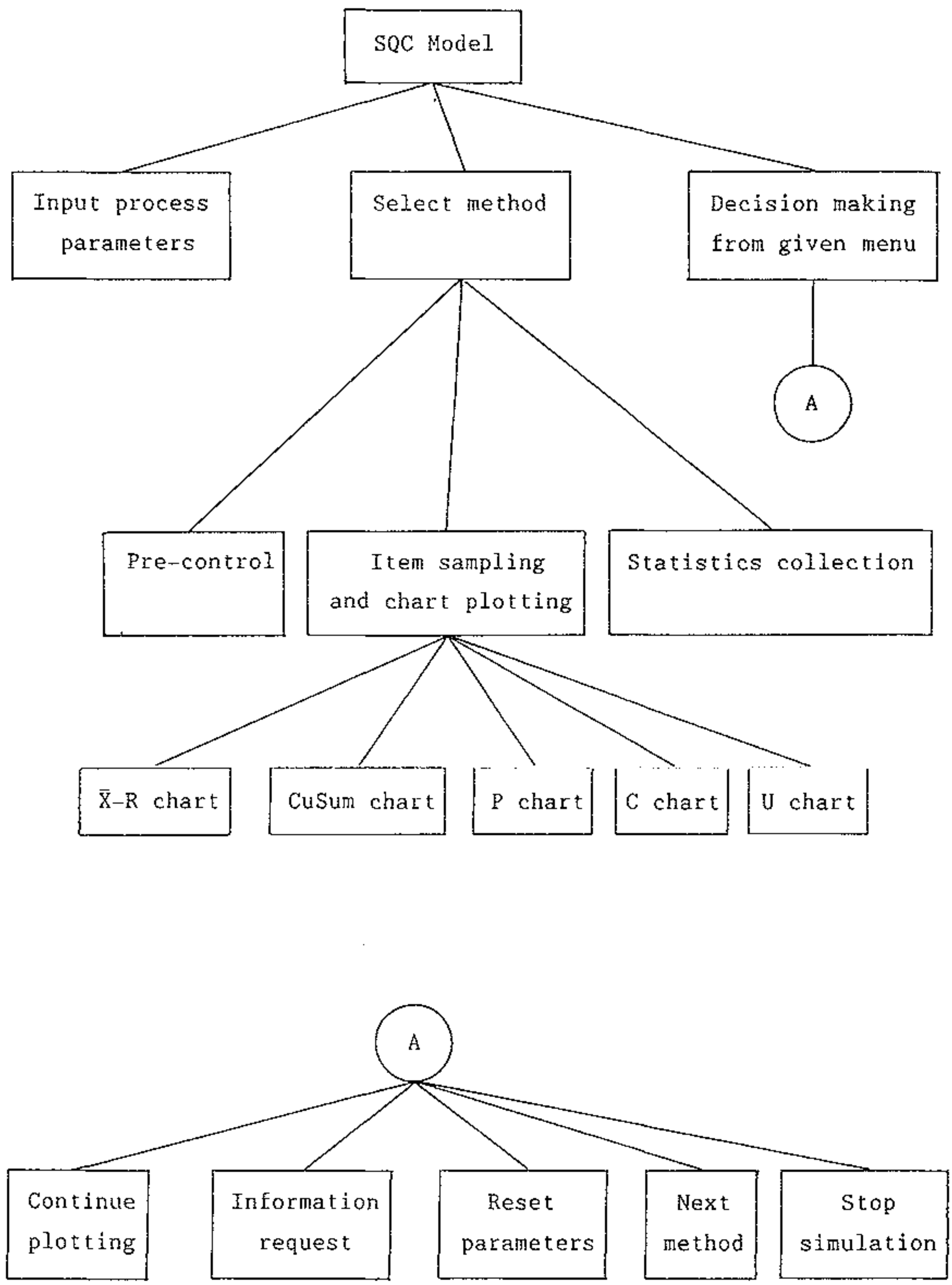

Figure 3.1 SQC model structure

3.3 Program Specifications

3.3.2 Select samples from provided distribution

- For $\bar{X}$-R chart and P chart : items are generated from normal distribution.

- For C and U charts :

  - o number of defects is generated from Poisson distribution.

  - o where appropriate number of inspection units is generated from uniform distribution.

3.3.3 Calculate statistics :

- For $\bar{X}$-R chart and P chart : in case either of these two methods is selected, all relevant statistics will be collected as follows :-

  - o average of each sample

  - o range of each sample

  - o fraction non-conforming

  - o total number of 'out-of-spec' items including those from sampling intervals

  - o cumulative fraction of non-conforming including those from sampling intervals

- o average of sample mean
- o average of ranges
- o average of fraction non-conforming
- o process capability ratio (PCR)

$$\text{where} \quad PCR = \frac{USL - LSL}{6\sigma}$$

- o control limits of both $\bar{X}$-R chart and P chart. In case of P chart with variable sample size, statistics calculation for $\bar{X}$-R chart is omitted. The following values are calculated instead :-

  - o average of sample size where individual sample size is produced within the range given by user.
  - o average control limits

- For C chart

  - o total number of defects
  - o average number of defects
  - o control limits

- For U chart

  - o total number of defects
  - o average number of defects per unit inspection where the individual number of defects are produced within the given range.

- o control limits at the i^{th} sample

- o average control limits

- For Standardized P chart and U chart : the following vaiables are converted into standard normal distribution with mean = 0 and standard deviation = 1

  - o average fraction of non-conforming for P chart or avarage number of defects per unit inspection for U chart

  - o control limits

3.3.4 Plot the setup chart on the screen

- o The program simulation consists of two phases of chart plotting :

  3.3.4.1 Setup phase : This phase is for chart setting up using an appropriate number of samples chosen by users. In this phase, all parameters can be adjusted until it is satisfactory.

  3.3:4.2 Implementing phase : After the chart has been already set up, the program is designed to simulate the performance of the process based on the setup chart. It allows users to make decisions via the given menu.

- o the program starts to plot the chart as setup phase after the first m samples are taken (generated).

o then during implementing phase, after a sample is taken, it will be plotted one at a time.

3.3.5 Allow user to judge control measures and make decision :

3.3.5.1 to continue plotting

or 3.3.5.2 to request information display

or 3.3.5.3 to reset parameter(s)

3.3.6 Produce summaries of all data produced in a run by

o displaying requested information on the screen

o storing requested information onto a file with name given by user

3.3.7 Repeat same runs of values for different SQC methods with the feature to allow user to control process parameters and methods.

3.4 Data and file specifications

All parameters and some variables, that are global to some relevant program modules, are defined in common block files shown in Appendix 4 and 5. There are 3 types of data used in program SQC :-

3.4.1 Input parameters are data required by the program depending on user's choices. Each input parameter is accepted into the program as alphanumeric string so that non-numeric value can be detected and hence input of the exponent format is not allowed. Appendix 3 describes input specifications.

3.4.2 Constant parameters are all constants defined by the program for some purposes i.e. maximum capacities of some variables and the text screen and graphic screen setting (See details in Appendix 3).

3.4.3 Output variables keep all output statistics informations produced by the program in forms of :-

- 2-dimensional array that keeps information for screen display and terminal-format file. (See output format in Appendix 3).

- Output file, with name specified as 'INFORMATION.FILE', which stores all primary data produced in a run. This file is ASCII coded format which cannot be read on the terminal screen. The data stored in this file is intended to be processed for other purposes later on. (See output format in Appendix 6).

CHAPTER 4

PROGRAM IMPLEMENTATION

SQC is a user interactive program which enables the user to judge control measures and adjust process parameters as required under the provided conditions. A program manual is essential for the user to communicate with and/or take action to the program responses.

Apart from the manual, example session will help users to be visualized how the program works and how the outputs are presented.

How to run SQC program

4.1 SQC is invoked by the following command :

```
RUN  SQC
```

4.2 Users will be prompted with

```
************************************
*  S  Q  C   S I M U L A T I O N  *
************************************

    Today's date : dd-mmm-yy
    Start time   : hh:mm am/pm
```

4.3 Then next input request is control chart method with the following prompts :-

```
Valid seeds must be integer and lie between 1 - 32767
Enter seed1  =
      seed2  =
      seed3  =
```

Users will be asked to enter starting seeds one by one. Then the users will be asked to select the method from the following menu :

```
Available control chart methods :
1.  Pre-control
2.  Xbar-R chart
3.  CuSum chart
4.  P chart
5.  C chart
6.  U chart
```

4.4 The next input prompts are input parameters depending on the selected method (See Appendix 5 for required input types). The prompts shown here are all possible input parameters available in this program.

```
Enter Mean                   =
      Standard deviation     =
      Number of samples for setup phase  =
      Sample size            =
      Upper range of inspection units/sample size  =
      Lower range of inspection units/sample size  =
      Inter-sampling number of items  =
      Lower spec. limit      =
      Upper spec. limit      =
```

Every time after finishing accepting input, the program will ask whether users would like to change or recorrect entered input as follows :

```
Re-correct parameters values.....(Y/N)
```

- o If Y, program will go back to ask for entering input again. Default for unchanged parameters is 'press <Enter>'.

- o If N, which is default, then press <Enter> and the program will procede.

4.5 After all required input has been entered, the program will go to the graphic screen, start to draw the chart and plot the samples one by one. During the setup phase, the program will not accept any interuptions, until the first m samples selected by user as 'number of samples for setup phase' are already plotted. Then the option menu is displayed on the right hand corner of the screen (see figures 4.1 to 4.11 for screen layout of each chart).

The cursor is always prompted by default in the form of '+' at the end of first choice Continue. If the user's choice is other than the default one, it can be accessed by moving the 'cursor' up or down using <↑> or <↓> on the keyboard.

The function of each option is

4.5.1 **Continue** : if this option is selected, the program will continue to generate a new sample and plot the point.

4.5.2 **Information** : if this option is selected, the program will go to text screen. At the beginning of the display, all input parameters legend will be presented. (See information format layout in Appendix 8). Then user is prompted to choose the optional number of displayed lines on the screen with

Enter frequency of number of sample(s) to be displayed
(not > ii)....Otherwise hit <Enter> for menu

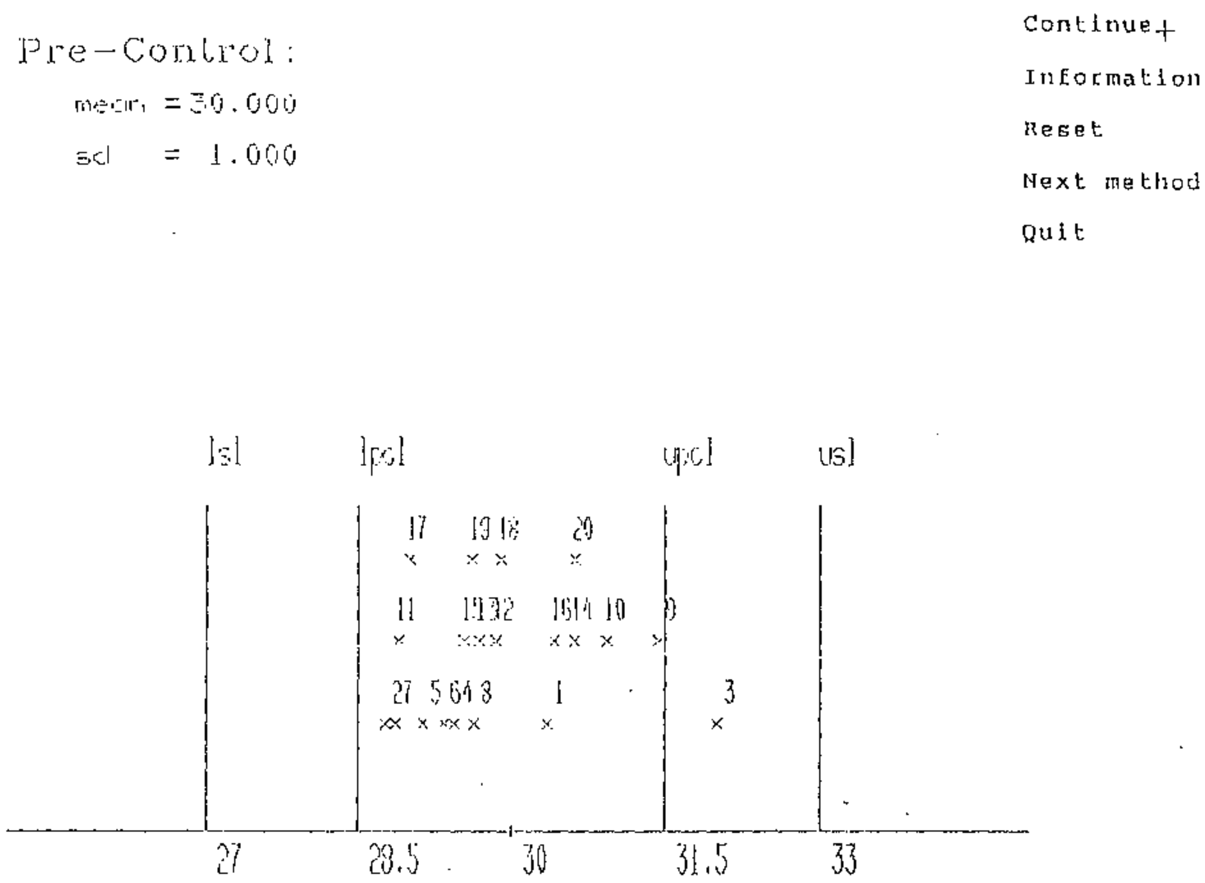

Figure 4.1 Screen layout of Pre-control chart

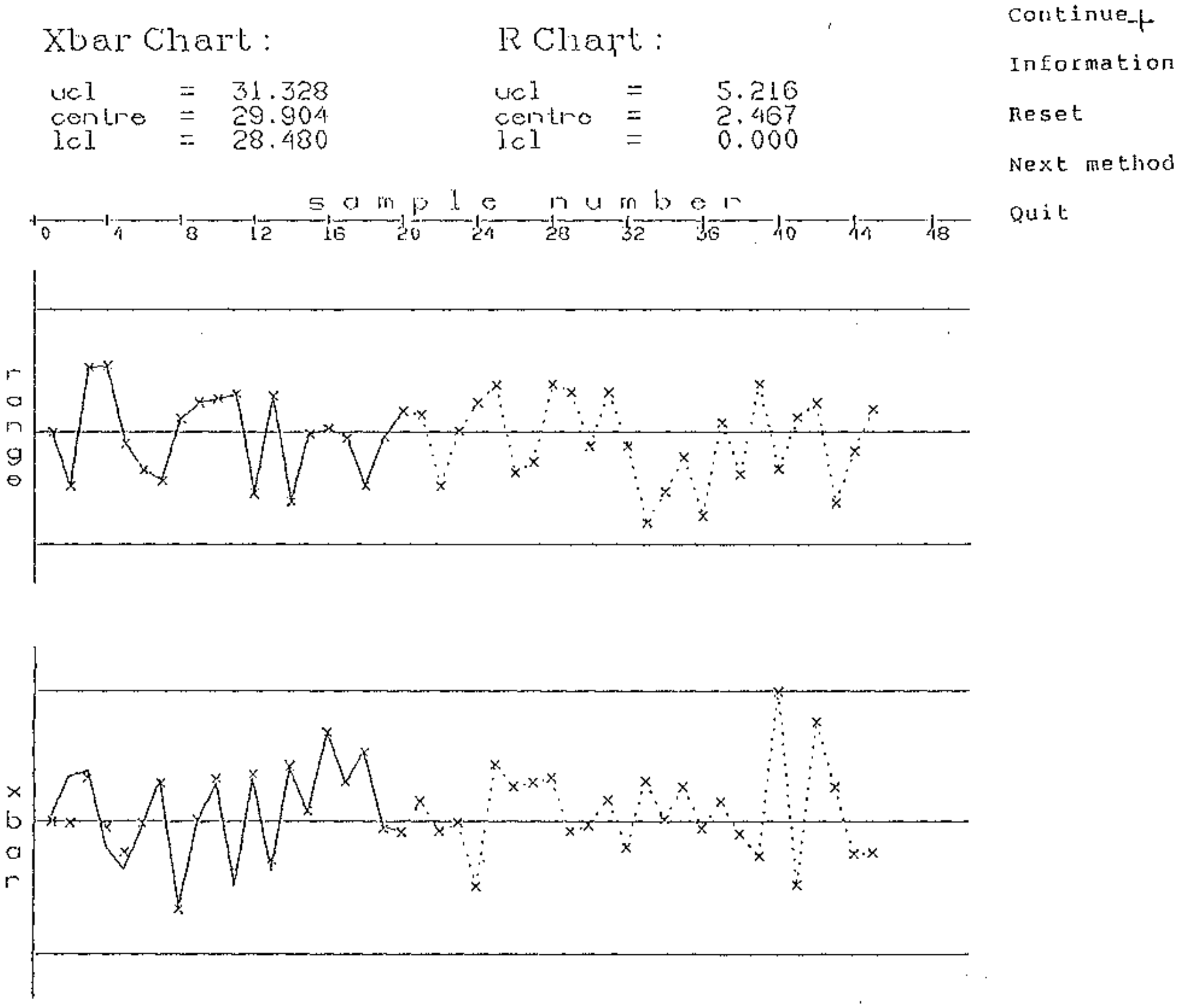

Figure 4.2 Screen layout of $\bar{X}$-R chart

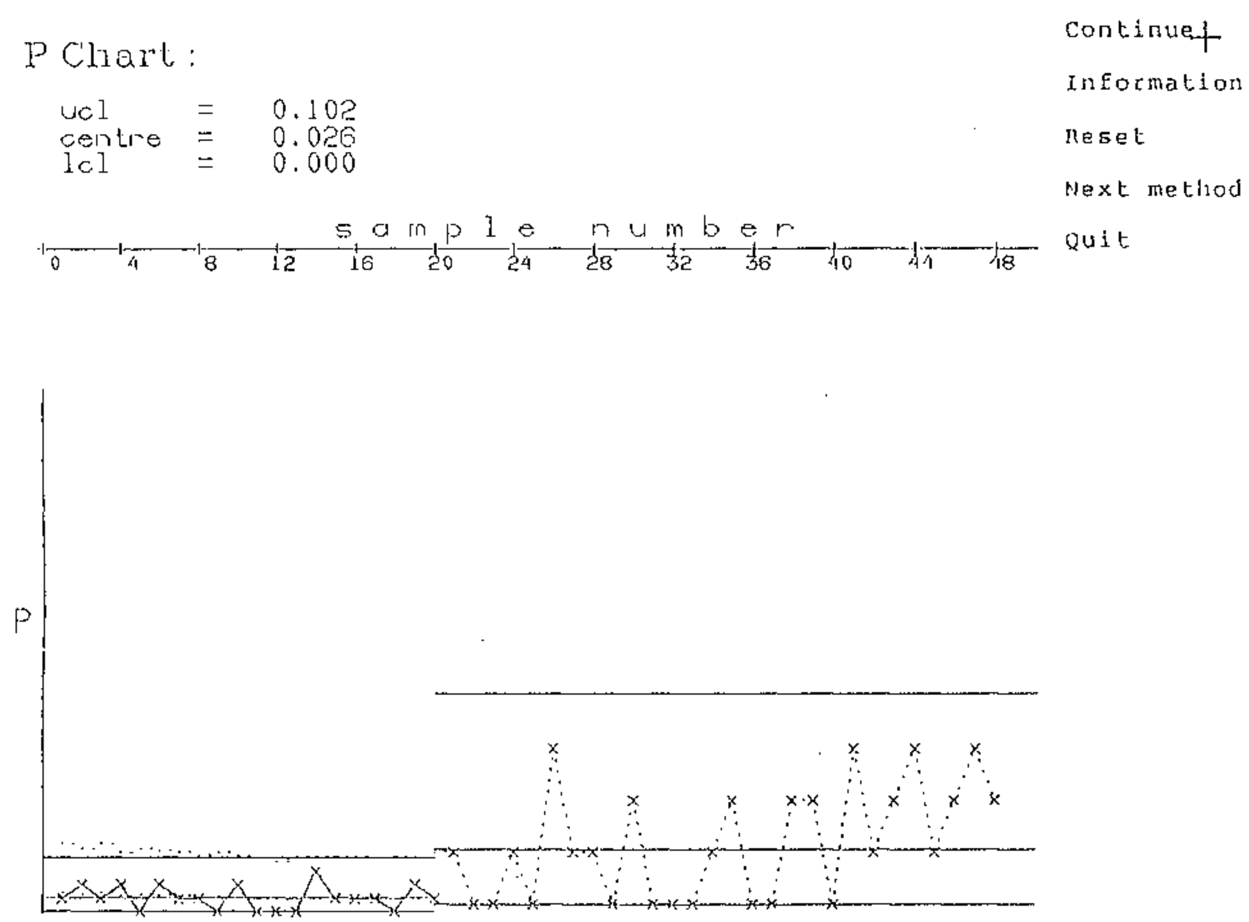

Figure 4.3 Screen layout of P chart with fixed sample size

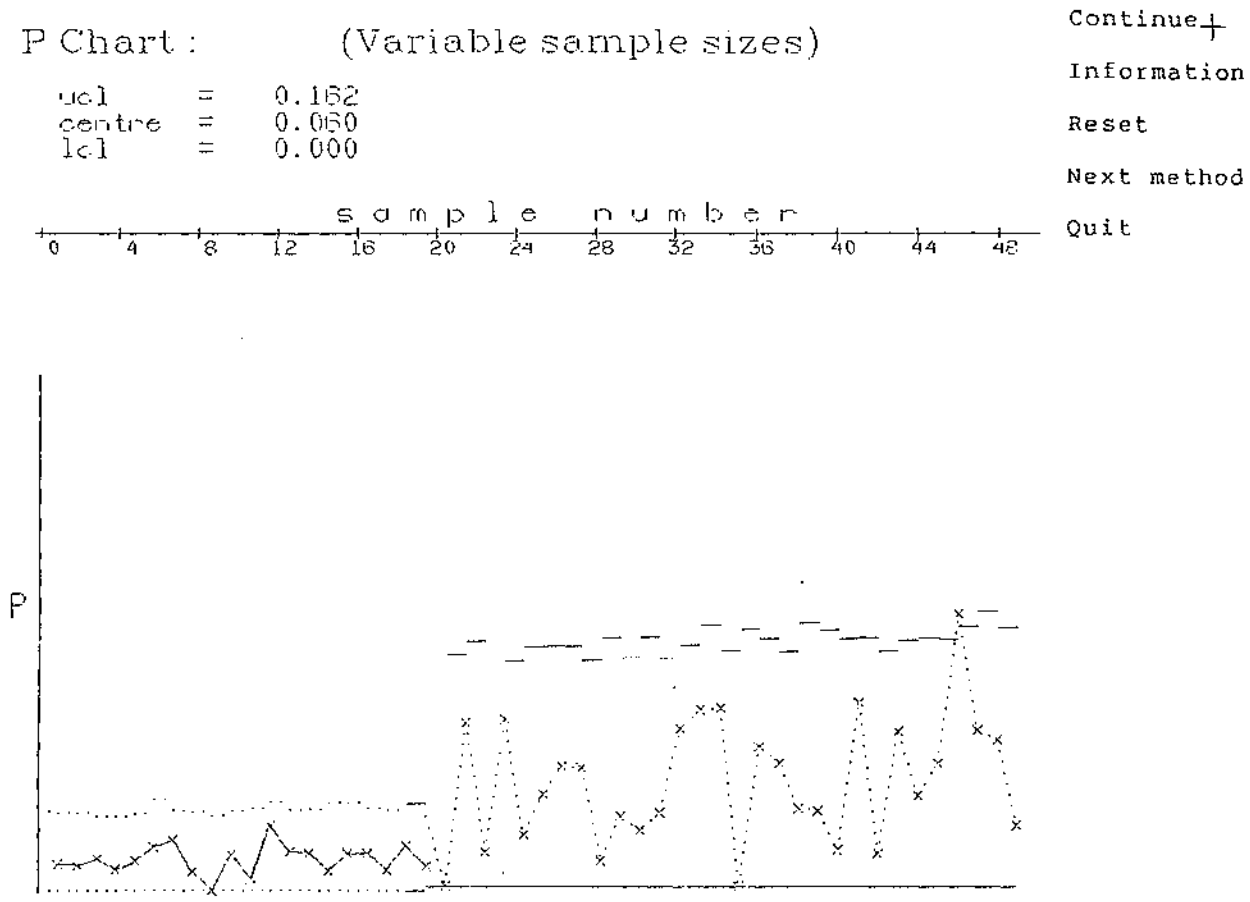

Figure 4.4 Screen layout of P chart with variable sample size

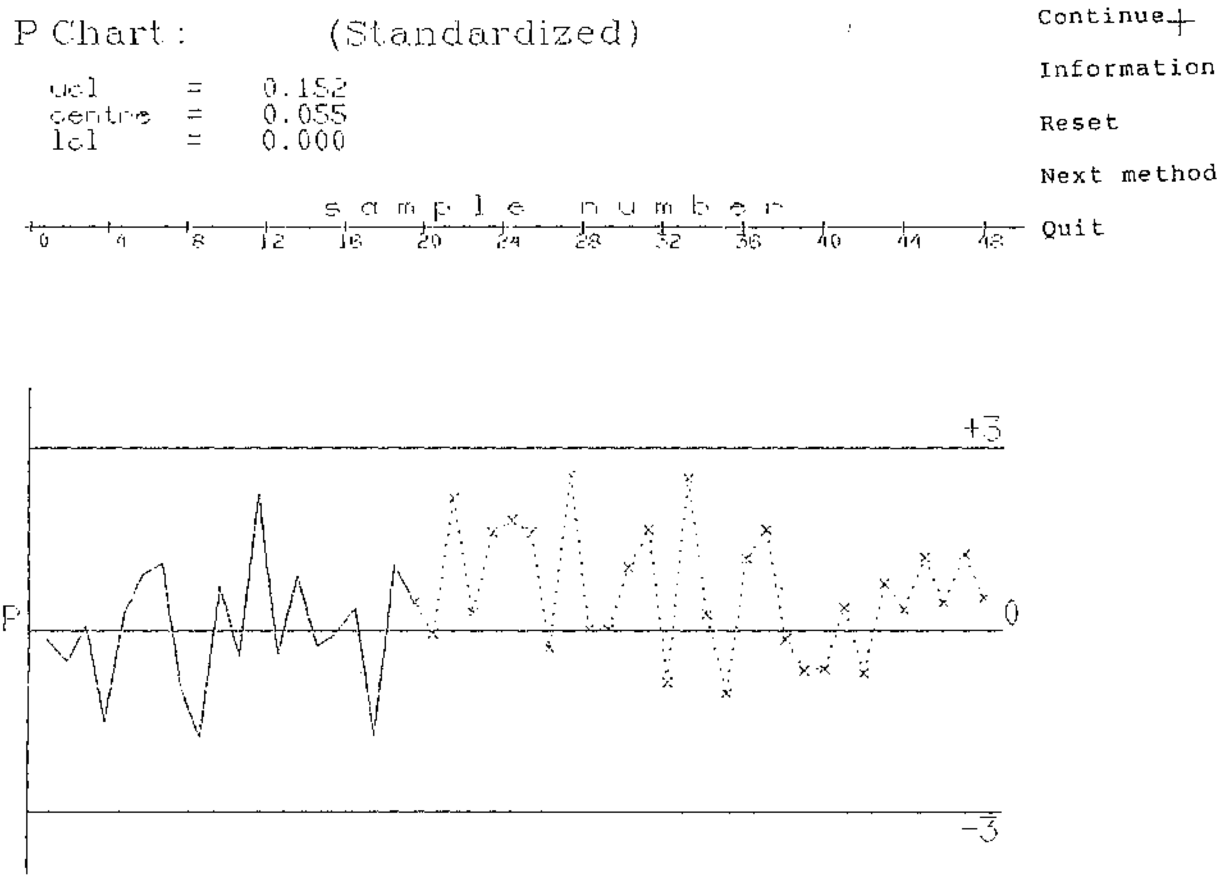

Figure 4.5 Screen layout of standardized P chart

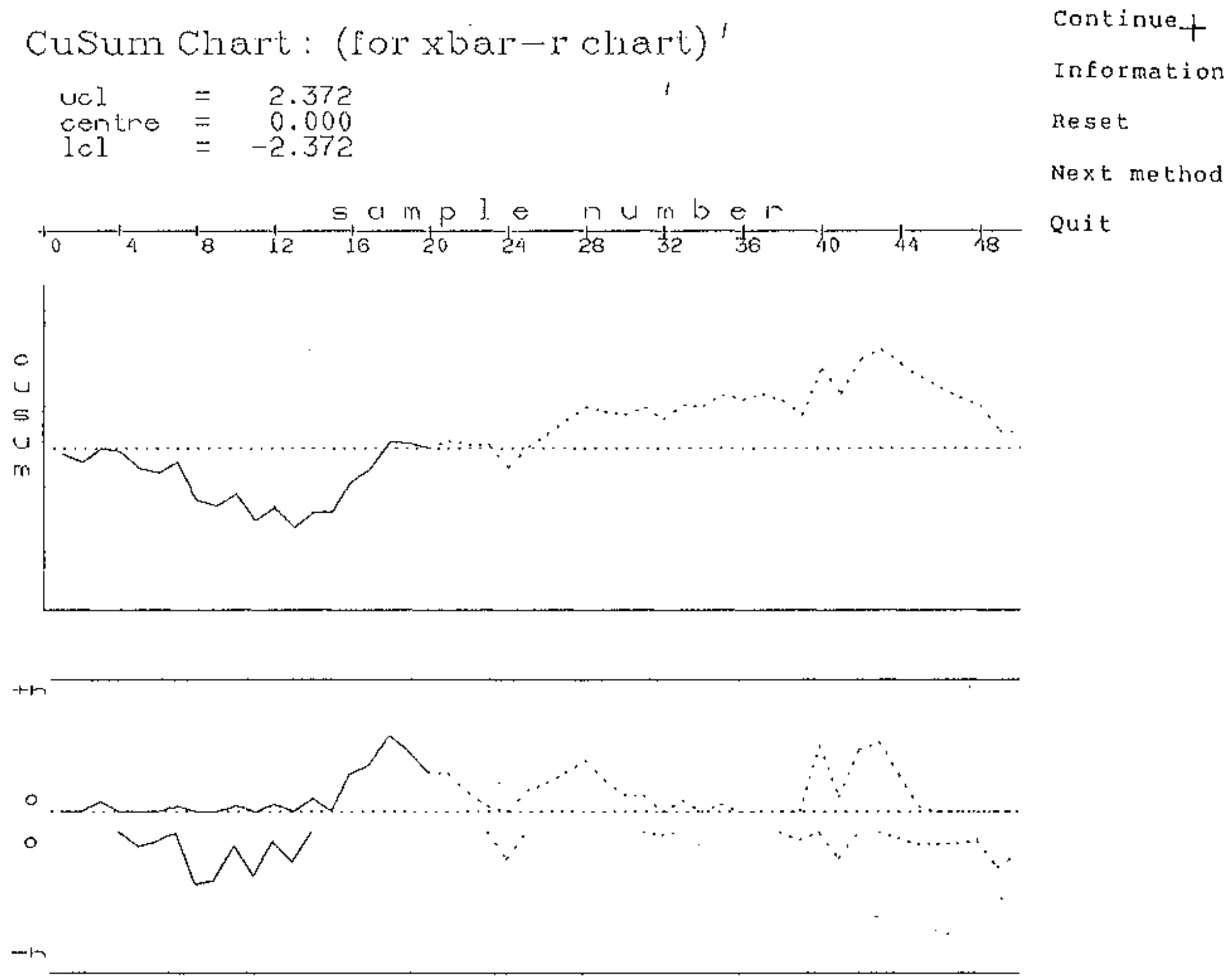

Figure 4.6 Screen layout of CuSum applied to $\bar{X}$ chart

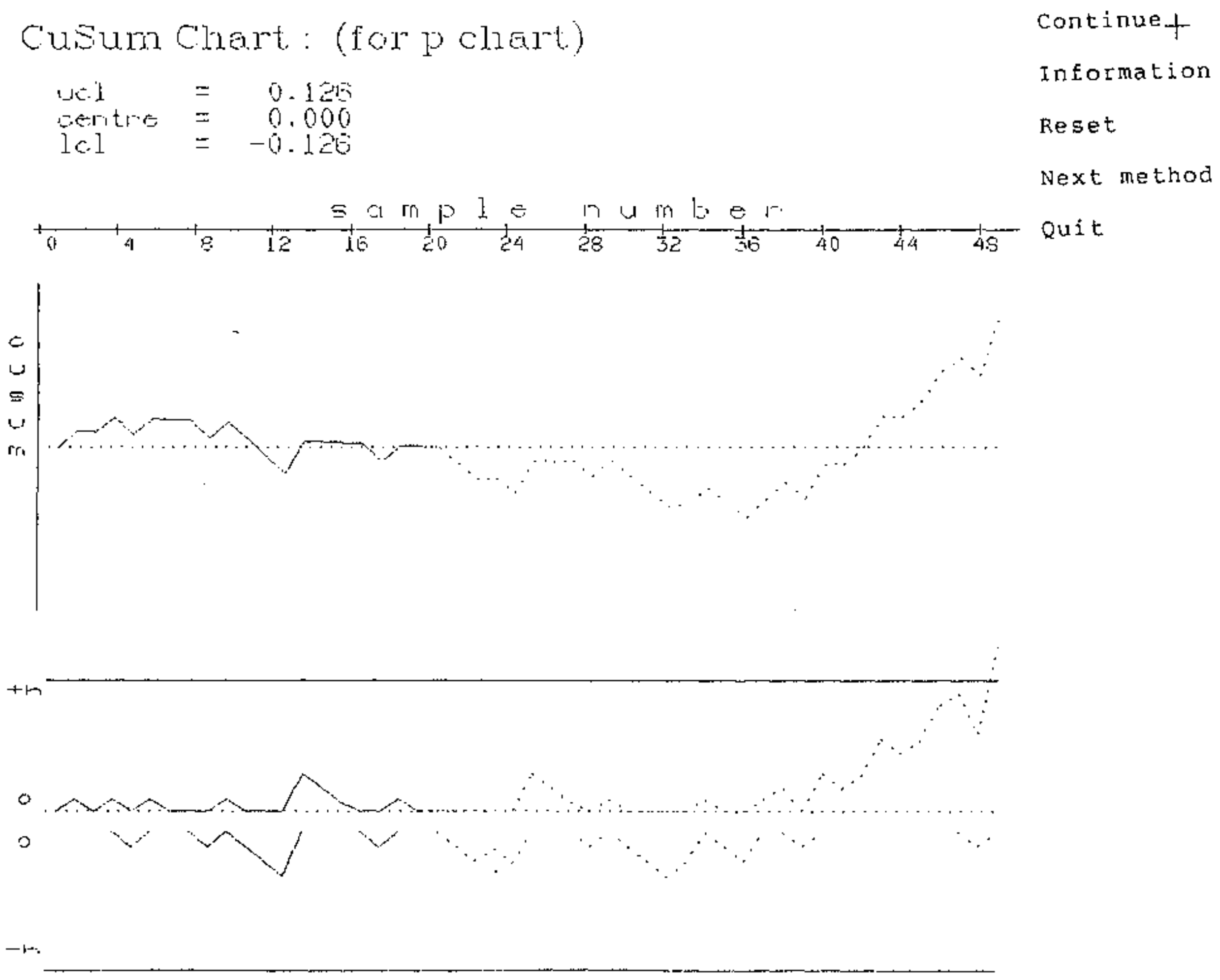

Figure 4.7 Screen layout of CuSum applied to P chart

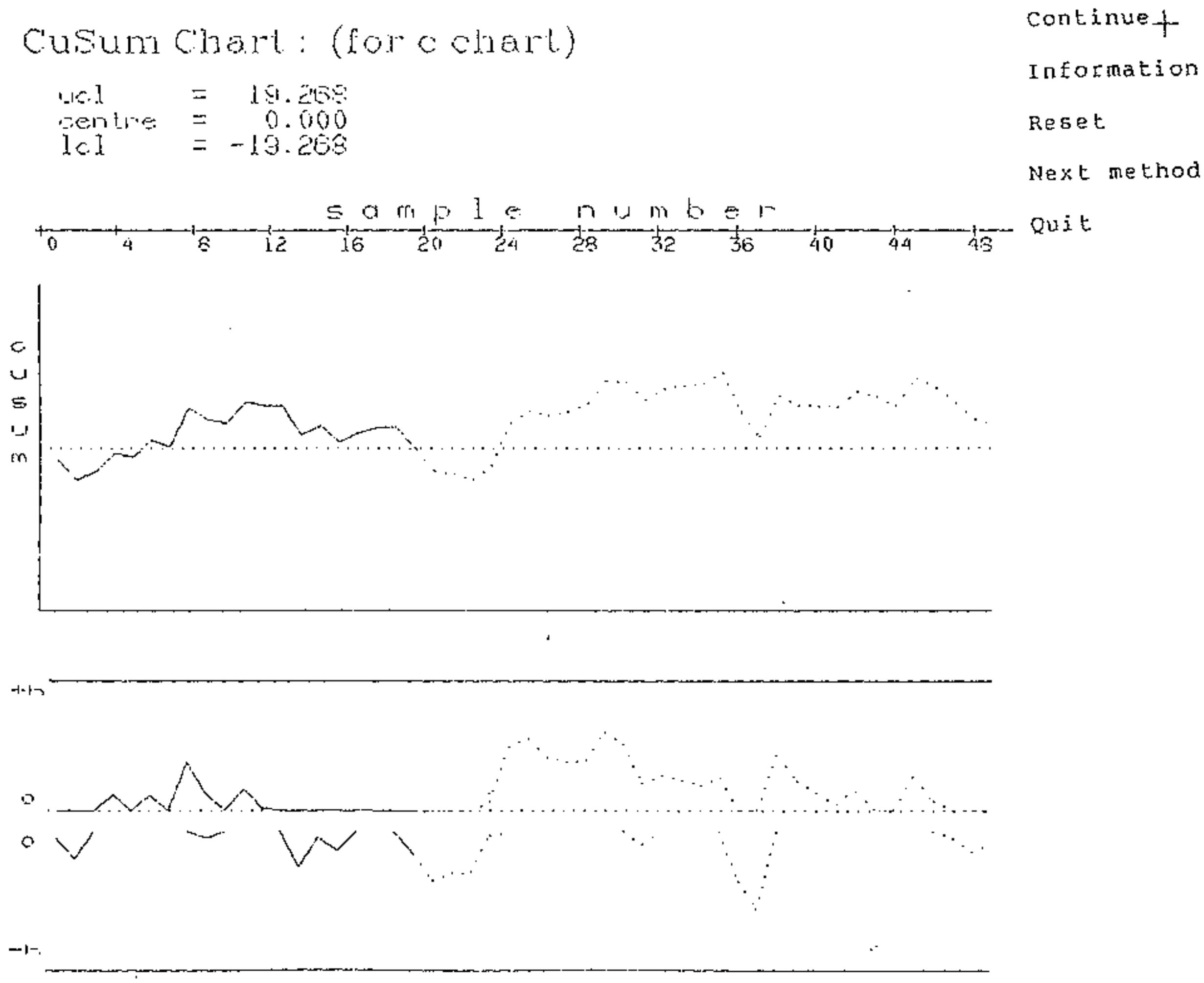

Figure 4.8 Screen layout of CuSum applied to C chart

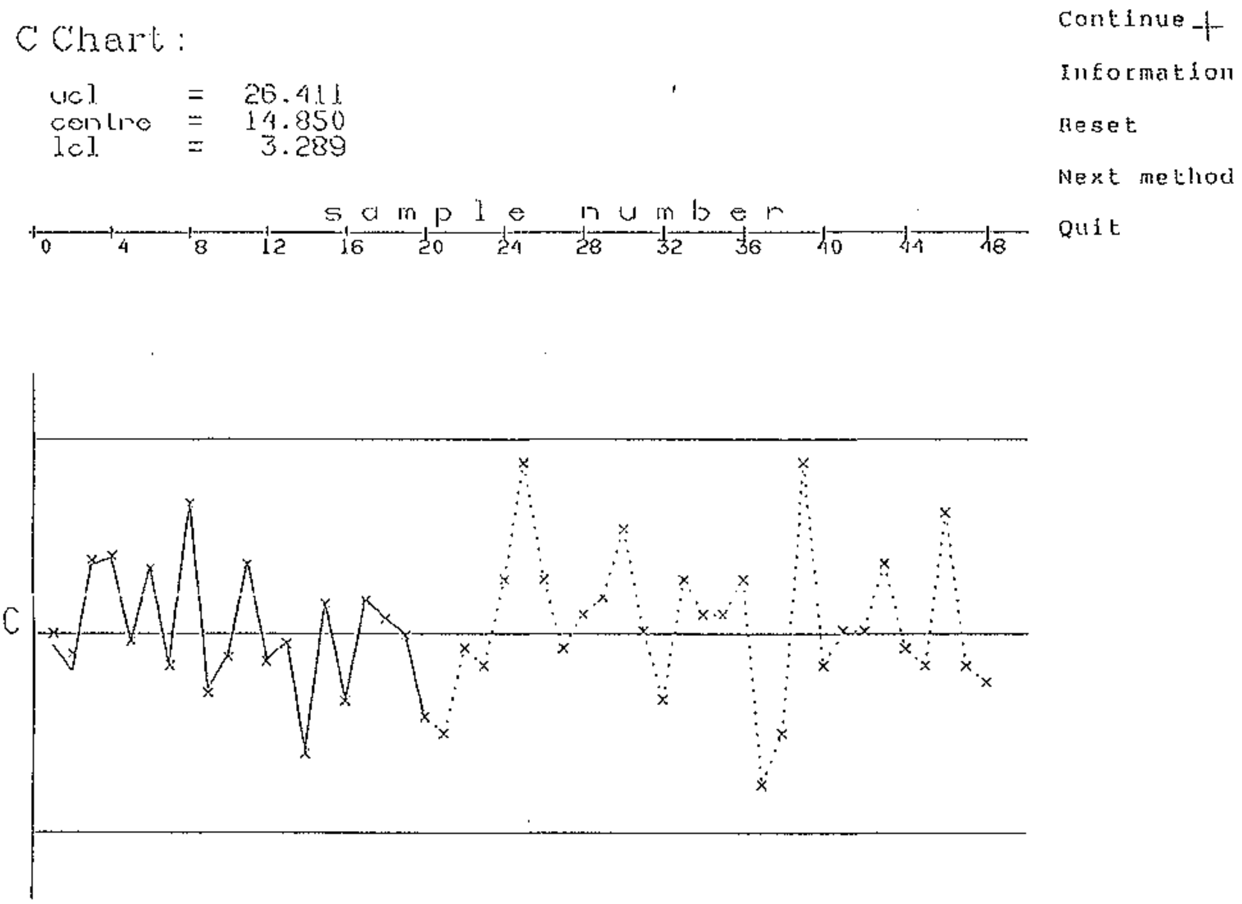

Figure 4.9 Screen layout of C chart

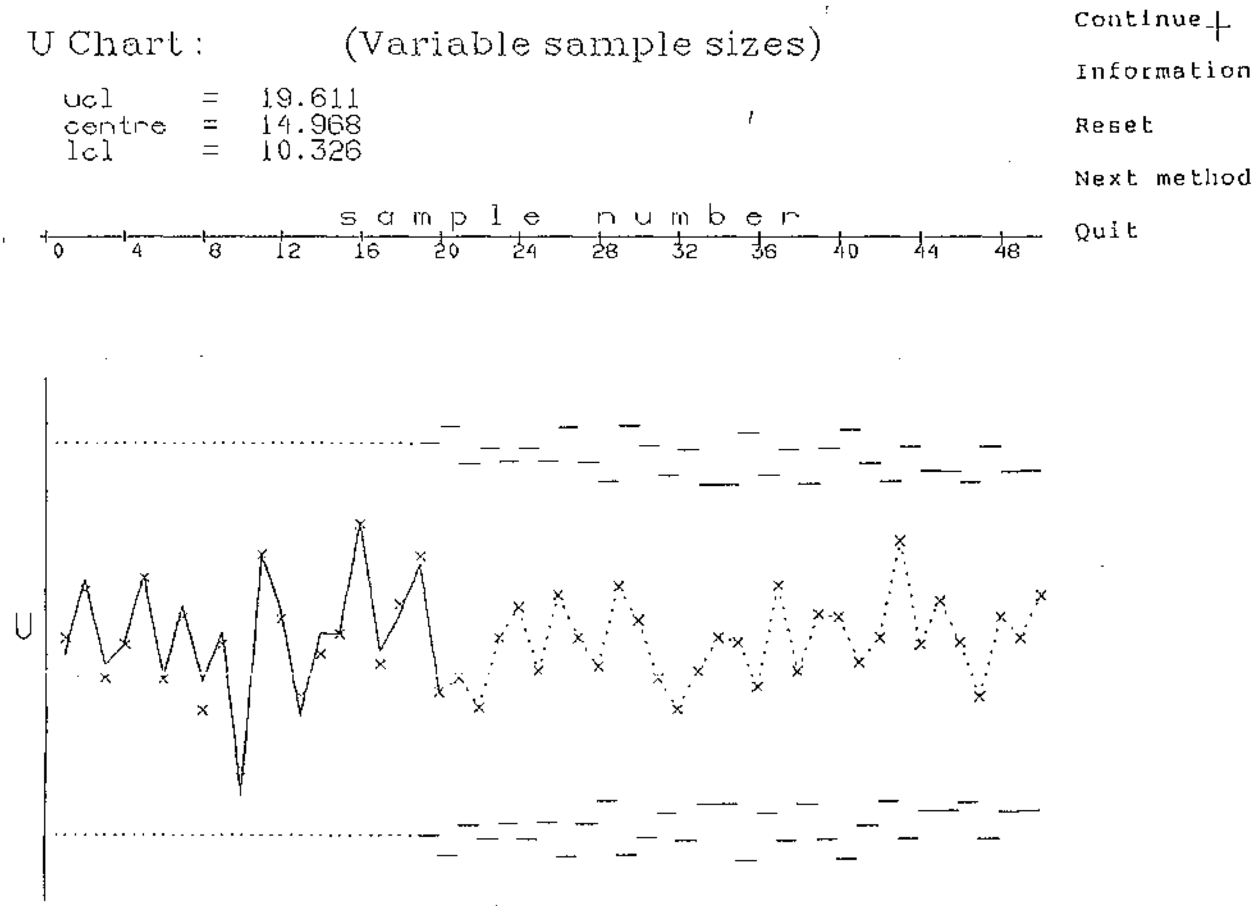

Figure 4.10 Screen layout of U chart

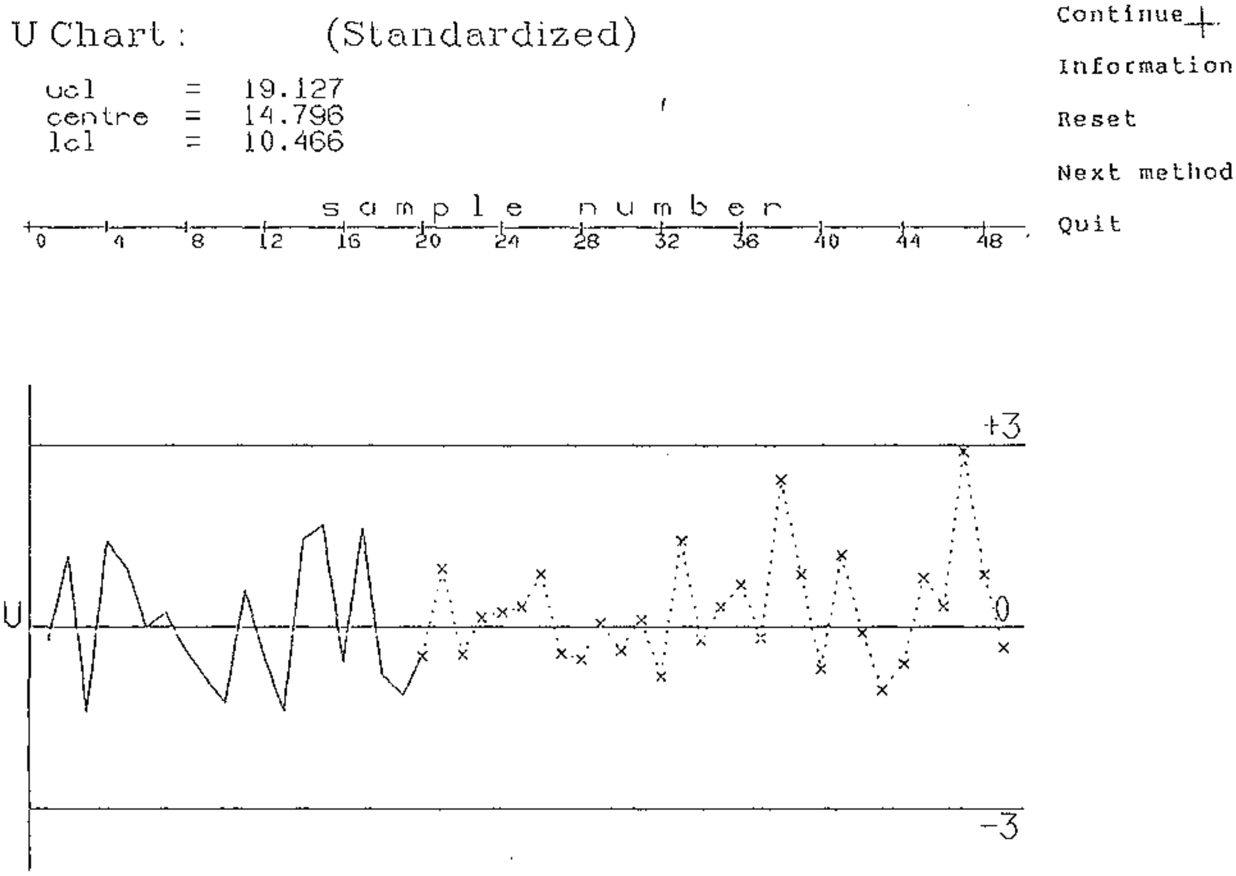

Figure 4.11 Screen layout of standardized U chart

For whatever value of i is set, then every i^{th} line will be displayed where the default value of i is 1.

If there are more than 12 lines of information to be displayed on the screen, the program will stop every 12 lines or at the of the information list with

More.....(M)
Quit.....(Q)

- o If M, the program will continue displaying for the next 12 lines or until the end of information in case the remaining lines are less than 12.
- o If Q, the program will respond with the prompt shown below.

At the end of the information display, user will be prompted with

Re-display the information.........(R)
Write information onto a file......(W)
Return to graphic screen...........(B)

- o If R, the program will go back to follow 4.5.2.
- o If W, user will be prompted with

Enter filename to store information under =

After the file has been written, the user will be informed with

File <filename> written.........

where 15 characters is the maximum length allowed for the name of the file and note that whenever the process parameters are reset, all previous information will be deleted and start to count the next sample as the first sample after parameter resetting.

o If B, the program will go back to graphic screen and prompt with the menu at the default option of Continue.

4.5.3 Reset : the program will go to text screen then

- For Pre-control :

  Enter Mean =
  Sd =

- For other methods : the following menu is presented to user

Select 'reset' option :-
1 : Reset with new CLs and replot from the 1st sample
2 : Reset without changing CLs and continue plotting
3 : Reset and continue plotting with new CLs
4 : Leave out off-limit sample(s) without changing CLs
5 : Leave out off-limit sample(s) with new CLs
6 : Return to graphic screen

o If 1, the program will initialize all variables, accept new process parameters from user, calculate new statistics and control limits, refresh the screen and plot the new-parameters chart from the setup phase, i.e. start from the beginning.

- o If 2, the program will accept new process parameters and continue plotting without calculating new control limits.

- o If 3, the program will accept new process parameters, calculate new control limits without refreshing the screen but draw new control limits with dash lines (----) and from now on the statistics will be compared with new control limits.

- o If 4, it is assumed that there are one or more sample(s) falling outside control limits, the program will leave out off-limit sample(s), re-order the sample number, refresh the screen and redraw the chart with re-ordered samples without calculating new control limits.

- o If 5, the same as choice 4 but the new control limits will be calculated.

- o If 6, the program will return to graphic screen.

4.5.4 **Next method** : the program will go to text screen and go back to 4.4, follow the same procedure. In addition, before prompting for accepting new parameters the previous values of involved input parameters are displayed and ask whether the user want to change the values.

Change initial seeds?......(Y/N) for input seeds and

Change parameters ?........(Y/N) for other input

- o If Y, the procedure will be the same as 'Re-correct' procedure in 4.4. However, all involved parameters will be checked to see if they are valid for the new chosen method before plotting.

- o If N, the program will procede to the plot procedure. In case the new selected method is in the same group (See the explanation in program specifications) as the previous one, the program will also ask whether or not to keep previous calculated samples.

Restore previous information...(Y/N)

- o If Y, this option is meaningful when the more than 'full_axis' (i.e. 50 samples, See data description in Appendix 3) have been plotted in the previous method because the program will plot only the latest page of the chart. Therefore if the user want to observe from the first sample, the next option will be more recommended.

- o If N, the program will start all procedures from 4.

4.5.5 Quit : the program will stop running and return control to the system by displaying :-

```
****************************************
*  E N D   O F   S I M U L A T I O N   *
****************************************

$ _
```

where $ is the VAX/VMS prompt.

4.6 Error and warning messages : Whenever invalid input is entered, the program will prompt the user with various display menus as follows :-

4.6.1 Warning message for negative seeds :-

*Warning : negative value is set to be positive...

4.6.2 Error messages for invalid inputs :-

Error type 1 : message for selected method is not within range 1 to 6.

*Error : invalid option <1 or >6...

Error type 2 : message for selected method applied to CuSum is not within range 1 to 3.

*Error : invalid option <1 or >3...

Error type 3 : message for out of specification mean and standard deviation defined in Appendix 3.

*Error : invalid mean...
*Error : invalid standard deviation...

Error type 4 : message for out of specification defined in Appendix 3.

*Error : the value <= 0 or exceeds maximum
capacity allowed in the system...
Re-enter......................(R)
Reset to default value........(D)

where default is the maximum capacity set to the system (see Appendix 3).

Error type 5 : message for non-numeric input parameters.

*Error : non-numeric data...

Error type 6 : message for upper range of unfixed sample size or unfixed inspection units that is less than or equal to lower or zero.

*Error : invalid range limits...

Error type 7 : message for upper specification that is less than or equal to lower specification or zero.

*Error : invalid specification limits...

Error type 8 : message for parameter values are invalid to intended chart when next method is selected.

*Error : invalid parameter value(s)...

Program validation

The program validation has been conducting by mean of 2 exercises, which also demonstrate how the program performs and what the summary results were (also see information screen display in Appendix 8).

Exercise 1

Tested methods are $\bar{X}$-R chart, P and CuSum chart applied to $\bar{X}$-R chart and P chart. The input process parameters (G. E. Smith, 1988; personal communication) are as the following :-

mean	=	30
standard deviation	=	1
items between samples	=	100
lower specification	=	27
upper specification	=	33

The summary output are shown in Table 4.1 , 4.2, 4.3 and 4.4. The results were discussed using two aspects, run lengths and process fraction non-conforming.

e1.1 Run lengths :

Run length is the average number of samples taken before an out-of-control signal is detected and can be used to determine how efficiently the control chart performs.

o For $\bar{X}$ chart :

If p is the probability of an out-of-control signal then

$$p = P(LCL > \bar{x} > UCL/\text{actual } \bar{x})$$

where UCL is upper control limit obtained from setup phase

Hence the average run length, ARL is defined by

$$ARL = \frac{1}{p} \qquad .....(4.1)$$

Table 4.1 shows the actual run lengths produced from the program compared with theoretical ARLs. It was found that the actual run lengths are close to the ARLs except those from small shift of 0.5 from target mean 30. This maybe because of the variations caused by the random number generator but is more likely to be because for small shifts both the ARL and standard deviation of RL are large.

o For CuSum chart :

The empirical approximation for the ARL at a certain shifted process where the observations have unit variance, has been developed by W. D. Evan and G. D. Kemp for one-sided sum scheme (Page, 1961). It is :

$$L_1 = 1 + \frac{h}{(\mu - k)} \qquad .....(4.2)$$

where L_1 = average run length before an out-of-control signal if noticed

h = decision interval

μ = process parameters that is regarded as bad should be detected quickly

k = reference value where the upper reference value was used here

The actual run length of the CuSum chart produced by the program are also around the theoretical ARLs (see Table 4.3) and similarly to the results of $\bar{X}$ chart, at the small shift of 0.5 from the target mean 30, the results were rather varied from the ARLs which were possibly caused by the variation from the random number generator as above.

Most of the program-produced fractions nonconforming were approximately prone to conform to the theoretical values. Comparing between $\bar{X}$-R chart and CuSum chart, the simulated results have been confirmed by many reports (e.g. Page (1961), Ewan (1963), Van Dobben de Bruyn (1968), Murdoch (1979), and Montgomery et al. (1987) that CuSum chart applied to $\bar{X}$ chart is more efficient than conventional $\bar{X}$ chart in detecting small shifts and the efficiency decreased as the shifts were getting larger. (See Table 4.2). While CuSum chart is effective when it is applied to $\bar{X}$ chart, it seems not to be so when it is applied to P chart (see Table 4.4), as the CuSum tended to detect the small shifts slower than conventional P chart.

Table 4.1 Summary results of actual run lengths in $\bar{X}$ chart of 5 different-seeds runs compared with theoretical average run lengths (ARLs)

		run #1		run #2		run #3		run #4		run #5	
sample size	actual mean	ARL	actual run	ARL	actual run	ARL	actual run	ARL	actual run	ARL	actual run
	30.5	57.47	6	34.01	14	181.82	18	14.97	13	58.82	107
	31.0	7.49	4	5.36	6	16.19	6	3.24	2	5.43	7
4	31.5	2.19	0	1.84	0	3.39	6	1.45	0	1.85	0
	32.0	1.23	0	1.16	0	1.48	0	1.07	0	1.16	0
	32.5	1.21	0	1.02	0	1.08	0	1.01	0	1.02	0
	30.5	24.45	15	31.06	19	147.93	426	58.82	81	9.97	26
	31.0	3.78	4	4.30	4	11.40	17	6.40	12	2.29	1
5	31.5	1.45	0	1.54	0	2.47	3	1.84	0	1.20	0
	32.0	1.06	0	1.07	0	1.23	0	1.12	0	1.02	0
	32.5	1.00	0	1.00	0	1.02	0	1.01	0	1.00	0
	30.5	17.53	28	10.15	7	21.97	5	9.60	17	30.40	29
	31.0	2.77	2	2.10	6	3.12	2	2.07	0	3.65	0
6	31.5	1.24	1	1.14	0	1.29	0	1.13	0	1.38	0
	32.0	1.02	0	1.01	0	1.02	0	1.01	0	1.03	0
	32.5	1.00	0	1.00	0	1.00	0	1.00	0	1.00	0

Table 4.2 Summary results of actual run length compared between $\bar{X}$ chart and CuSum chart applied to $\bar{X}$ chart

test		actual run length					
run #	actual	$\bar{X}$ chart			CuSum chart		
	$\bar{X}$	4	5	6	4	5	6
1	30.5	6	15	28	4	5	4
	31.0	4	4	2	2	2	2
	31.5	0	0	1	1	1	1
	32.0	0	0	0	1	1	1
	32.5	0	0	0	1	0	1
2	30.5	14	19	7	15	5	6
	31.0	6	4	6	4	2	2
	31.5	0	0	0	2	1	1
	32.0	0	0	0	1	0	1
	32.5	0	0	0	0	0	0
3	30.5	18	426	5	8	17	5
	31.0	6	17	2	5	6	2
	31.5	6	3	0	3	3	1
	32.0	1	0	0	2	1	0
	32.5	0	0	0	1	1	0
4	30.5	13	81	17	15	5	3
	31.0	2	12	0	2	2	1
	31.5	0	0	0	1	1	1
	32.0	0	0	0	1	0	0
	32.5	0	0	0	0	0	0
5	30.5	107	26	29	7	5	3
	31.0	7	1	0	3	2	1
	31.5	0	0	0	2	1	1
	32.0	0	0	0	1	1	0
	32.5	0	0	0	1	0	0

Table 4.3 Summary results of actual run lengths in CuSum chart of 5 different-seeds runs compared with theoretical average run lengths (ARLs)

		run #1		run #2		run #3		run #4		run #5	
sample size	actual mean	ARL	actual run	ARL	actual run	ARL	actual run	ARL	actual run	ARL	actual run
	30.5	10.81	4	10.94	15	18.78	8	7.69	15	8.95	7
	31.0	4.44	2	4.21	4	5.32	5	3.62	2	4.09	3
40	31.5	3.09	1	2.91	2	3.46	3	2.63	1	2.92	2
	32.0	2.50	1	2.36	1	2.72	2	2.18	1	2.39	1
	32.5	2.17	1	2.06	0	2.32	1	1.92	0	2.09	1
	30.5	11.10	5	7.61	5	7.21	17	12.30	5	5.89	5
	31.0	3.81	2	3.76	2	3.78	6	4.28	2	3.16	2
60	31.5	2.63	1	2.75	1	2.79	3	2.92	1	2.39	1
	32.0	2.15	1	2.28	0	2.32	1	2.35	0	2.02	1
	32.5	1.89	0	2.01	0	2.05	1	2.05	0	1.81	0
	30.5	5.97	4	5.08	6	6.78	5	5.41	3	8.11	3
	31.0	3.32	2	3.05	2	3.44	2	3.04	1	3.63	1
80	31.5	2.51	1	2.37	1	2.56	1	2.32	1	2.61	1
	32.0	2.12	1	2.03	1	2.13	0	1.98	0	2.16	0
	32.5	1.89	0	1.82	0	1.89	0	1.78	0	1.91	0

Table 4.4 Summary results of actual run length compared between P chart and CuSum chart applied to P chart

test run #	actual X̄	P chart 40	P chart 60	P chart 80	CuSum chart 40	CuSum chart 60	CuSum chart 80
1	30.5	2	8	86	396	99	102
	31.0	2	1	5	2	3	1
	31.5	0	0	0	0	0	0
	32.0	0	0	0	0	0	0
	32.5	0	0	0	0	0	0
2	30.5	57	9	1	25	9	19
	31.0	5	9	1	5	4	1
	31.5	2	0	0	2	1	0
	32.0	0	0	0	0	0	0
	32.5	0	0	0	0	0	0
3	30.5	34	12	0	34	12	0
	31.0	0	0	0	0	1	0
	31.5	0	0	0	0	0	0
	32.0	0	0	0	0	0	0
	32.5	0	0	0	0	0	0
4	30.5	11	1	4	5	0	41
	31.0	3	0	0	3	0	1
	31.5	0	0	0	1	0	0
	32.0	0	0	0	0	0	0
	32.5	0	0	0	0	0	0
5	30.5	6	4	11	7	31	3
	31.0	3	0	0	3	3	1
	31.5	0	0	0	1	1	1
	32.0	0	0	0	0	1	1
	32.5	0	0	0	0	1	1

e1.2 Fraction nonconforming :

Table 4.5 shows the summary results of the cumulative fraction nonconforming from repeated runs of 5 different seed groups compared with theoretical fraction of nonconforming which are the probability that the process falls outside specification given actual process average for overall process (i.e. including sampling interval). However, the run results were not be able to compare with the theoretical ones because the run results were not collected suitably for statistics tests but for observing how the method performed especially when the input parameters were varied in each run.

Let p be the fraction nonconforming

then $p = P(LSL=27 > x > USL=33 / \text{actual } \bar{x})$

where USL is the upper specification limit
LSL is the lower specification limit

Table 4.5 Summary results of cumulative percent defectives produced from various sample sizes

test run #	actual $\bar{X}$	theoretical fraction of nonconforming	$\bar{X}$-R chart			P chart		
			4	5	6	40	60	80
1	30.0*	0.0026	0.002	0.002	0.002	0.004	0.003	0.004
	30.5	0.0062	0.012	0.007	0.006	0.005	0.005	0.006
	31.0	0.0228	0.033	0.032	0.025	0.024	0.025	0.020
	31.5	0.0668	0.029	0.038	0.066	0.071	0.069	0.067
	32.0	0.1587	0.154	0.133	0.142	0.171	0.181	0.194
	32.5	0.3085	0.298	0.295	0.340	0.321	0.338	0.311
2	30.0*	0.0026	0.003	0.003	0.003	0.003	0.003	0.004
	30.5	0.0062	0.004	0.005	0.004	0.006	0.007	0.008
	31.0	0.0228	0.015	0.015	0.020	0.024	0.021	0.031
	31.5	0.0668	0.048	0.048	0.038	0.055	0.088	0.083
	32.0	0.1587	0.183	0.162	0.142	0.157	0.138	0.144
	32.5	0.3085	0.346	0.286	0.245	0.314	0.275	0.283
3	30.0*	0.0026	0.002	0.002	0.002	0.003	0.003	0.003
	30.5	0.0062	0.010	0.007	0.014	0.007	0.007	0.017
	31.0	0.0228	0.033	0.029	0.057	0.036	0.025	0.039
	31.5	0.0668	0.073	0.083	0.075	0.086	0.050	0.089
	32.0	0.1587	0.163	0.095	0.123	0.193	0.113	0.144
	32.5	0.3085	0.269	0.257	0.311	0.379	0.338	0.294
4	30.0*	0.0026	0.002	0.002	0.002	0.002	0.002	0.003
	30.5	0.0062	0.006	0.006	0.006	0.005	0.013	0.004
	31.0	0.0228	0.013	0.016	0.009	0.014	0.025	0.022
	31.5	0.0668	0.048	0.067	0.057	0.050	0.050	0.056
	32.0	0.1587	0.144	0.190	0.189	0.186	0.131	0.133
	32.5	0.3085	0.346	0.390	0.368	0.293	0.306	0.272
5	30.0*	0.0026	0.002	0.002	0.002	0.002	0.002	0.001
	30.5	0.0062	0.005	0.005	0.004	0.001	0.005	0.004
	31.0	0.0228	0.024	0.019	0.009	0.016	0.013	0.028
	31.5	0.0668	0.058	0.038	0.028	0.064	0.094	0.072
	32.0	0.1587	0.106	0.067	0.094	0.193	0.194	0.144
	32.5	0.3085	0.260	0.257	0.274	0.336	0.319	0.306

* percent defectives were collected during first 20 samples of setup phase, not when the shift was detected

Exercise 2

Bommer and Frazer (1976) proposed an $\bar{X}$-R chart laboratory exercise written in Fortran. The data presented were :-

mean	= 100
standard deviation	= 5
sample size	= 5
lower specification limit	= 85
upper specification limit	= 115

Bommer and Frazer (1976) allowed the first 10 samples run with no change. The possible events in their simulation were jump shift in the mean, standard deviation and a trend generated in the mean which happened by generating a chance of occurring in percent of the time, i.e. if the generated random number, r is less than 0.05 the events will be generated as

$r<0.01$	: generate trend in mean with prob(up) = prob(down)
$r>0.04$	: generate increase in standard deviation from unit poisson distribution
$0.01<r<0.04$	: generate change in mean with prob(up) = prob(down)

The generated events and the reset actions were the sample numbers shown in Table 4.6.

Table 4.6 Summary results of generated changes and parameters reset in Bommer and Frazer (1976) 's simulation

sample	mean	std. dev.	type of events
32	95.49		change in mean
34	100		reset
54		8.84	change in std.
57		5	reset
79	100.65		trend in mean commence
80	101.3		
81	101.95		
82	102.6		
83	103.25		
84	103.9		
85	104.55		
86	105.2		
87	100		reset
93	100		reset

Since the SQC program used the different approach of setting rather than simulating parameters, the events were generated by using the 'RESET' option 2. Process parameters were reset without changing control limits following the sample numbers listed in Table 4.6. The results are presented as plotted charts shown in Figure 4.12 and compared with Bommer and Frazer's in Table 4.7 and Table 4.8 . The circled points were out-of-control samples detected by SQC and the squared ones were the first samples after process parameters were reset according to Bommer and Frazer's in Table 4.6. They showed that the SQC program detected the shift in ranges chart slower than Bommer and Frazer's and the trend in the mean did not cause any out-of-limit sample. Since the standard deviation in SQC is assumed to be not known and is estimated by $\bar{R}/d_2$ while standard deviation in Bommer and Frazer's is assumed to be known, the control limits in SQC needs to be wider.

Table 4.7 Comparison of the detected samples between the Bommerand Frazer's and the SQC program

type of events	at sample	detected sample or action taken on	
		Bommer-Frazer's	SQC's
change in mean	32	33	33
change in std.	54	57	62
trend in mean	79-86	87	92

Table 4.8 Comparison of the control limits from the Bommer and Frazer's and the SQC program

method	$\bar{X}$ chart		R chart	
	UCL	LCL	UCL	LCL
Bommer and Frazer's*	106.70	93.30	24.60	0
SQC**	107.86	91.94	29.16	0

* Computing 3-sigma limits for $\bar{X}$ and R based on population mean, $\bar{X}'$, with known standard deviation, σ', yields the following control limits :-

- For $\bar{X}$ chart :

  $$CLs = \bar{X}' \pm A\sigma'$$

  where A is factor of control limits for $\bar{X}$ chart when standard deviation is known

- For R chart :

  $$UCL = D_2\sigma'$$

  $$LCL = D_1\sigma'$$

  where D_1, D_2 are factors of control limits for ranges chart

** Computing 3-sigma limits for $\bar{X}$ and R chart with unknown standard deviation, yields the control limits already described in section 2.1.2, Chapter 2.

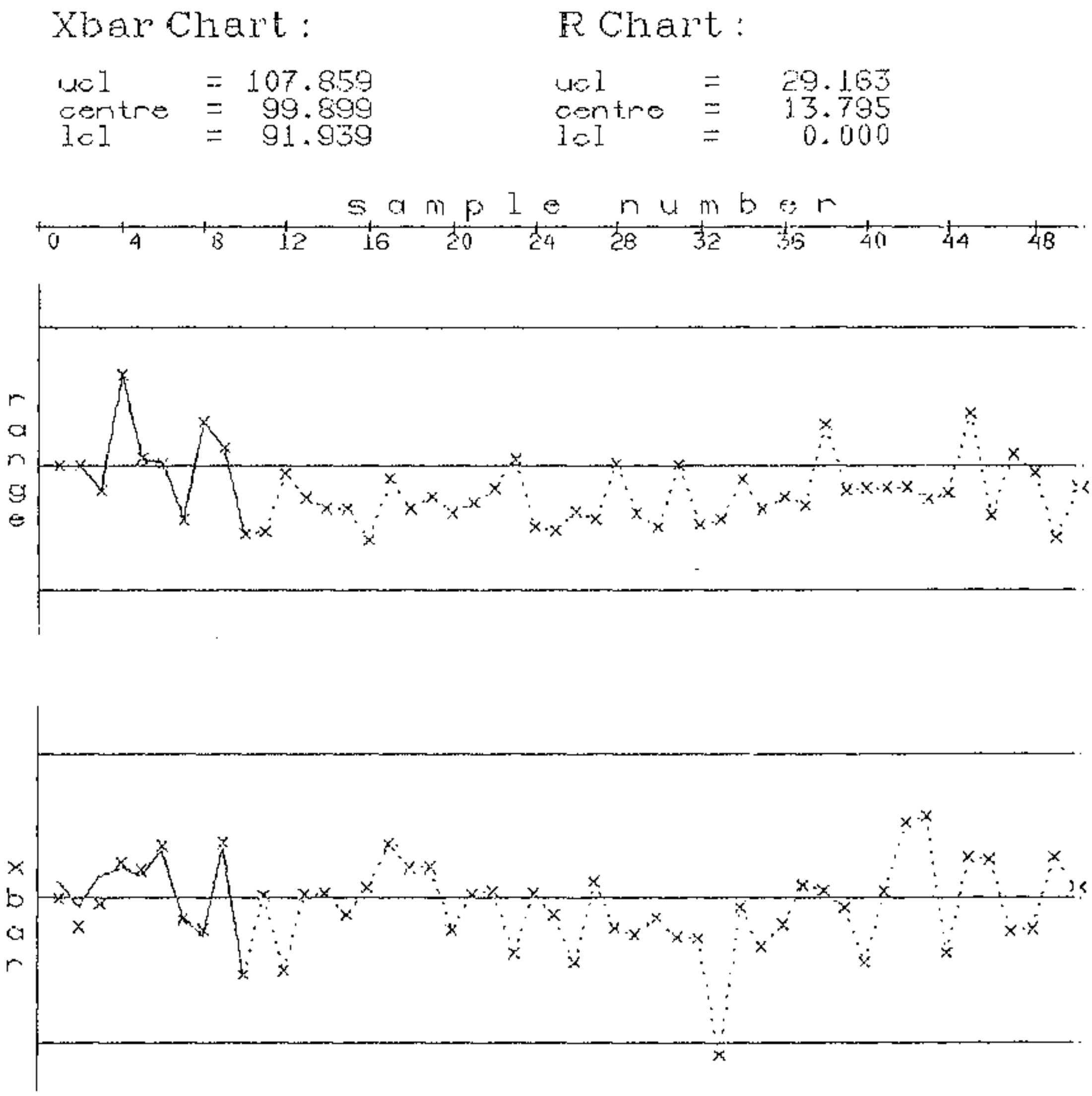

Figure 4.12 The output of $\bar{X}$-R chart plotted by SQC using input process parameters from Bommer and Frazer (1976)

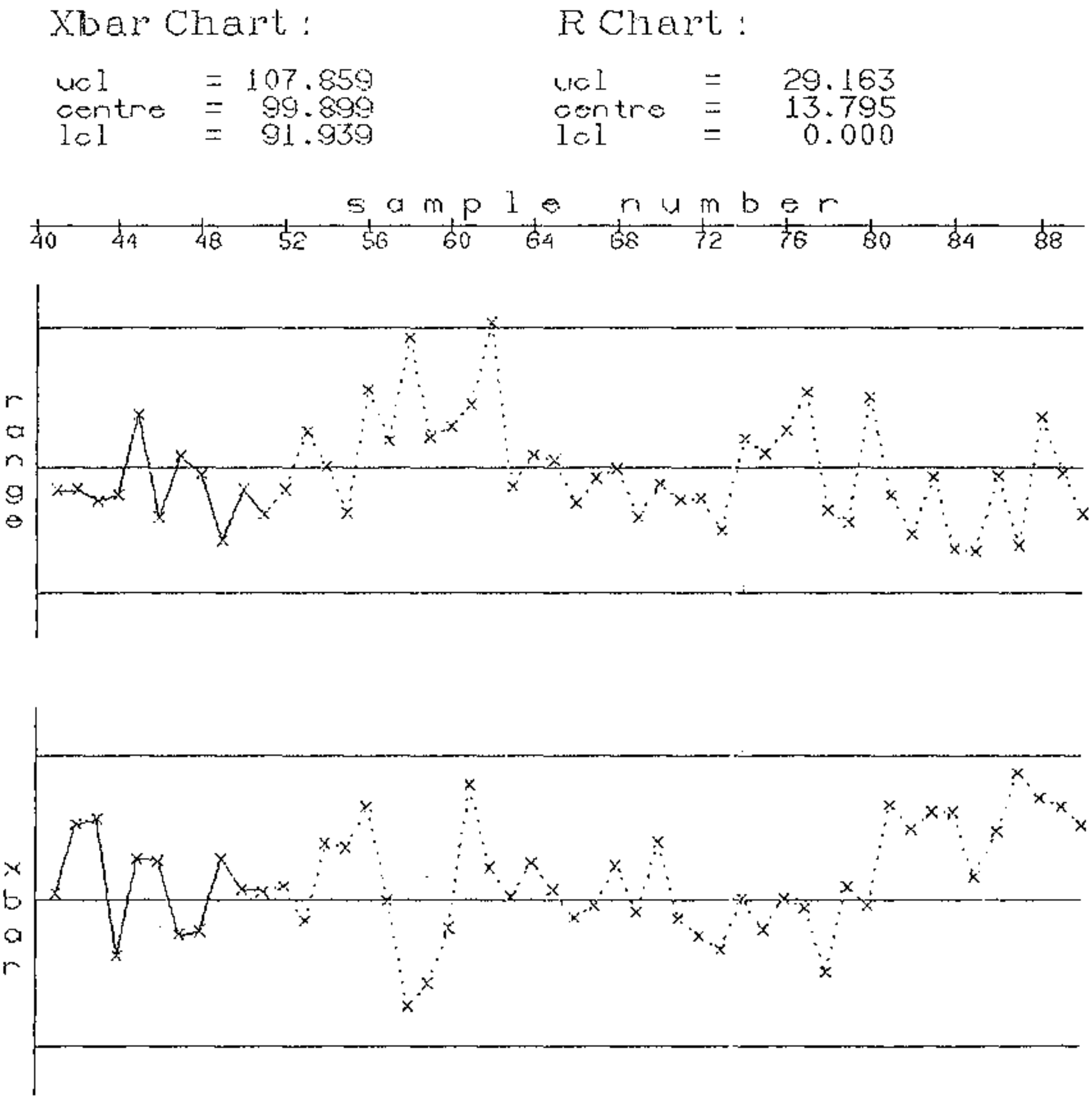

Figure 4.12 The output of X-R chart plotted by SQC using input process parameters from Bommer and Frazer (1976) (cont.)

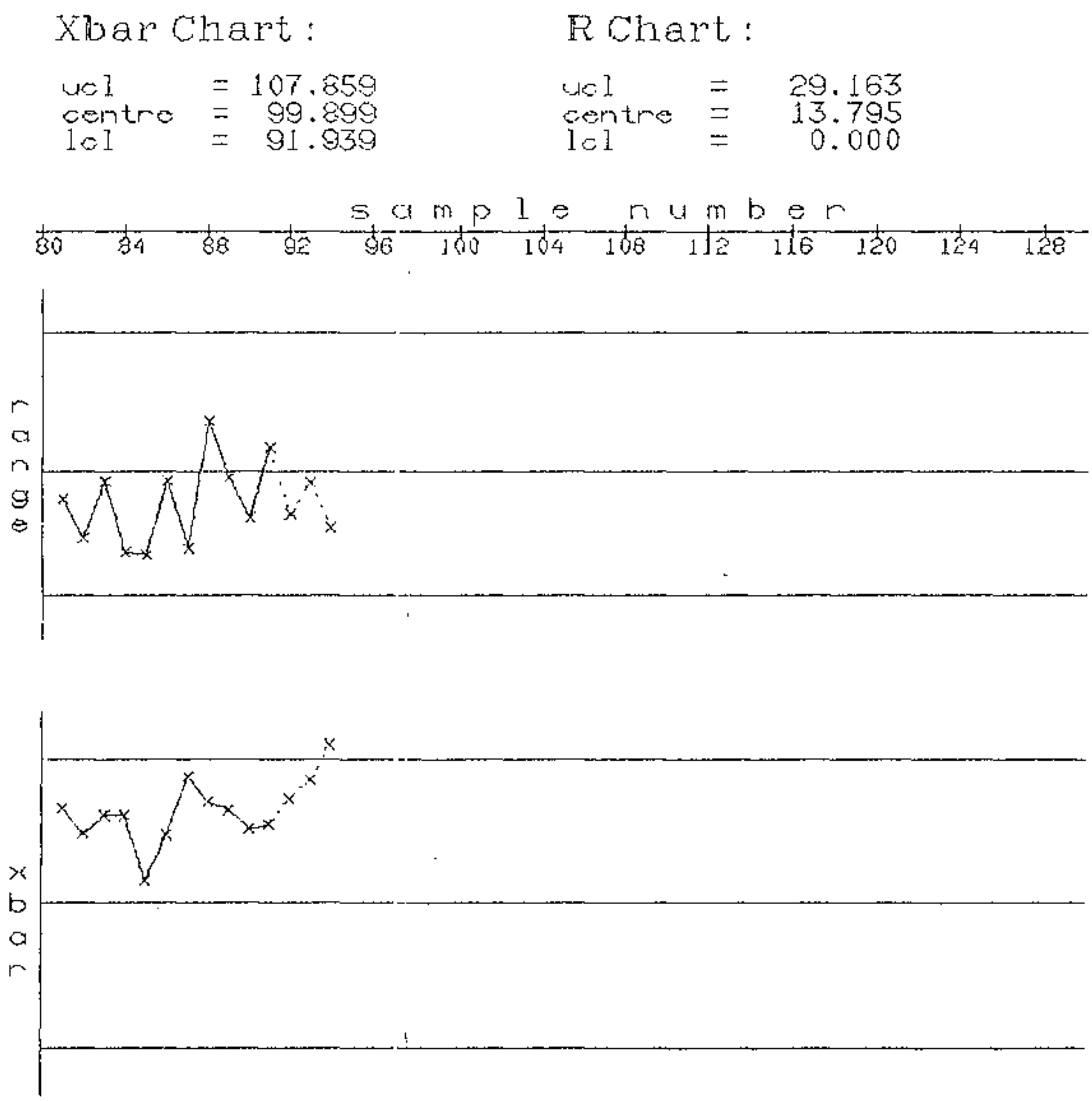

Figure 4.12 The output of X-R chart plotted by SQC using input process parameters from Bommer and Frazer (1976) (cont.)

CHAPTER 5

CONCLUSION AND SUGGESTION FOR FURTHER STUDY

1. SQC program

SQC was developed to simulate :-

- o data from production processes subject to inherent random variation with normal distribution and predetermined or random parameter changes.
- o sample selection for statistical quality control purposes.

1.1 Program capability

- o Produce summaries of all data in a run.
- o Select samples, calculate statistics.
- o Allow user to judge control measures required and adjust parameters if needed from 6 available control methods.
  - o Pre-control
  - o $\bar{X}$-R chart
  - o P chart
    - o fixed sample size
    - o unfixed sample size
    - o standardized
  - o C chart
  - o U chart
    - o unfixed sample size
    - o standardized
  - o CuSum chart applied to $\bar{X}$ chart, P chart with fixed sample size and C chart.

- o Repeat the runs for different control methods.
- o Store all data produced in various ways.
- o Provide the feature of user interactive control of process parameters.

1.2 However, the validation of some other methods, which are C chart and U chart, have not been carried out apart from the verification of the calculations and graph plotting that have been done by hand.

1.3 Hardware and software limitation

It is not quite convenient to run the SQC because the program has to change to and fro between text screen and graphic screen. The graphic feature of the VAX does not allow writing of long text while using the VAX BASIC graphics. In addition, the drawn windows of the graphic screen cannot be saved. As described in Appendix 1 there are many windows defined to use for various purposes on the same screen. Hence whenever one of the drawn windows needs to be changed, the whole screen has to be cleared and redrawn, no matter whether the windows are modified or not.

The other inconvenience is that the output filed format for the displayed information on the screen is fixed as xxxx.xxxx for floating point and xxxx for integer values as maximum values to be displayed on the 80-column screen in order to cover every essential output on the same line. Therefore the input value that is larger than this format should be transformed before using otherwise the output field will appear to be shifted and sometimes will be rounded off to a new excessive line.

2. Method used

2.1 Statistical techniques

2.1.1 The Poisson ramdom variate generator used in this program is a simple technique called 'sequential search technique'. Atkinson (1979) found that the technique is sufficiently accurate, but he also commented that the computation time would increase as μ increased.

2.1.2 In Chapter 4, Table 4.4, it was found that the results from small shifts were far different from the ARLs. This may have been because the suspectedly inherent variation of random number generator. However, the ARLs for small shifts are large and have large standard deviations, so that it is to be expected that actual run lengths will differ markedly from ARLs.

3. The suggestion for further development

3.1 The use of Poisson random generator technique suggested by Atkinson (1979). The technique is called 'Norman-and-Cannon algorithm (PNC)' which performed a fast speed of computation. In spite of its fast computing time, the disadvantages should be condisdered (i.e. low accuracy and the need of calculating the table and related constants), depending on how much accuracy and necessity the application needs.

3.2 Study of another approach to transformed P chart for variable sample size comparing with the present method. The method used in this program was standardized P chart which transformed all data to standard normal distribution N(0,1) (see details in Chapter 2). Soffer (1981) has proposed an approach to transformation with some advantages that the effects of variable n are mostly removed. There is no need for variable, approximate, or multiple central line or control limits as long as sample sizes are sufficiently large and cases of points that are marginally in or out of control show up more clearly on graphical display.

3.3 Adding some other interesting distribution of the process such as a bi-modal distribution. At present, the available distribution of process is normal distribution which was fixed in the sampling routine. The modification can be worked out by establishing a separate routine to pick up a selected distribution similarly to chart selecting routine.

3.4 Adding of some other interesting control charts. Montgomery et al. (1987) suggested that geometric moving average control chart (GMA) was also more effective than the usual $\bar{X}$ chart in detecting small shifts like the CuSum. Also the combined Shewhart GMA procedure and the combined Shewhart-CuSum control schemes can provide good protection against both small and large shifts (Lucas, 1983 and Montgomery et al.,1987).

3.5 Adding the feature of generating the events as in Bommer and Frazer's exercise. Since the happenings of the events in SQC program such as shift in mean or ranges depend on the physical generating nature of the random generators. This point will be good for students in quality control laboratory exercise and the program needs to be user interactive. However, the program can be modified to be run in batch feature for fundamental practice.

3.6 Finally acceptance sampling investigations of completed data are potentially possible area for program modification.

Generally, the results simulated by SQC were at acceptable level. The performances of the program on simulating data sampling and chart setting up are satisfactory at the stage of the first-time built package although there were quite a number of points that have not been validated statistically such as the performance of C and U charts and CuSum chart applied to P chart. This program can be utilized as a teaching tool for practising and experiencing how the quality control charts work or as a research tool for observing or studying the process control and improvement.

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APPENDIX 1

SQC PROGRAM MAINTENANCE

This part overviews how the program was established and how some important parts are carried out. For further details, see the VAX BASIC Reference and Manual (DEC, 1987a,1987b,1987c).

1. SQC Program Components

SQC comprises 3 major components (See Figure A1.1 for SQC structure and list of program modules in Appendix 7) :-

1.1 Main program

1.1.1 Main module : where main operations are performed.

- o Program initialization
- o Sampling simulation
- o Chart selection
- o Decision making

1.1.2 Local subroutines : are the routines that are in the same module as the statement that calls them. These routines are accessed by GOSUB statements. All variables used in these subroutines are global to the calling module.

1.1.3 Internal subprograms : this kind of subprogram is accessed by **CALL** statement and all variables used within are local except those defined in **Common** or **Map** block files (which are explained in section 1.3). They are accessed only by the module to which they are attached and are compiled along with the calling module.

1.2 External subprograms : these subprograms perform the same functions as internal subprograms. The difference is that they are compiled separately and independently and can be accessed by many modules.

1.3 Common and map block files : they are accessed by **%INCLUDE** statement at the beginning of each module. This statement will copy the predefined common or map block into that module where the predefined variables are use in common. (See Appendix 6). These files are created independently and do not need to be compiled in advance. However, whenever either the common block file or map block file is modified, every module that includes it must be re-compiled and all modules must be linked before running (program compilation and linkage are explained in section 2 and 3).

1.3.1 Common block file : all variables and constants used in common are defined under the **COMMON** statement.

1.3.2 Map block file : it is the record buffer defined under **MAP** statement. This buffer is used in recording the data produced from the simulation which are stored in an ASCII text file. (See map block format in Appendix 6).

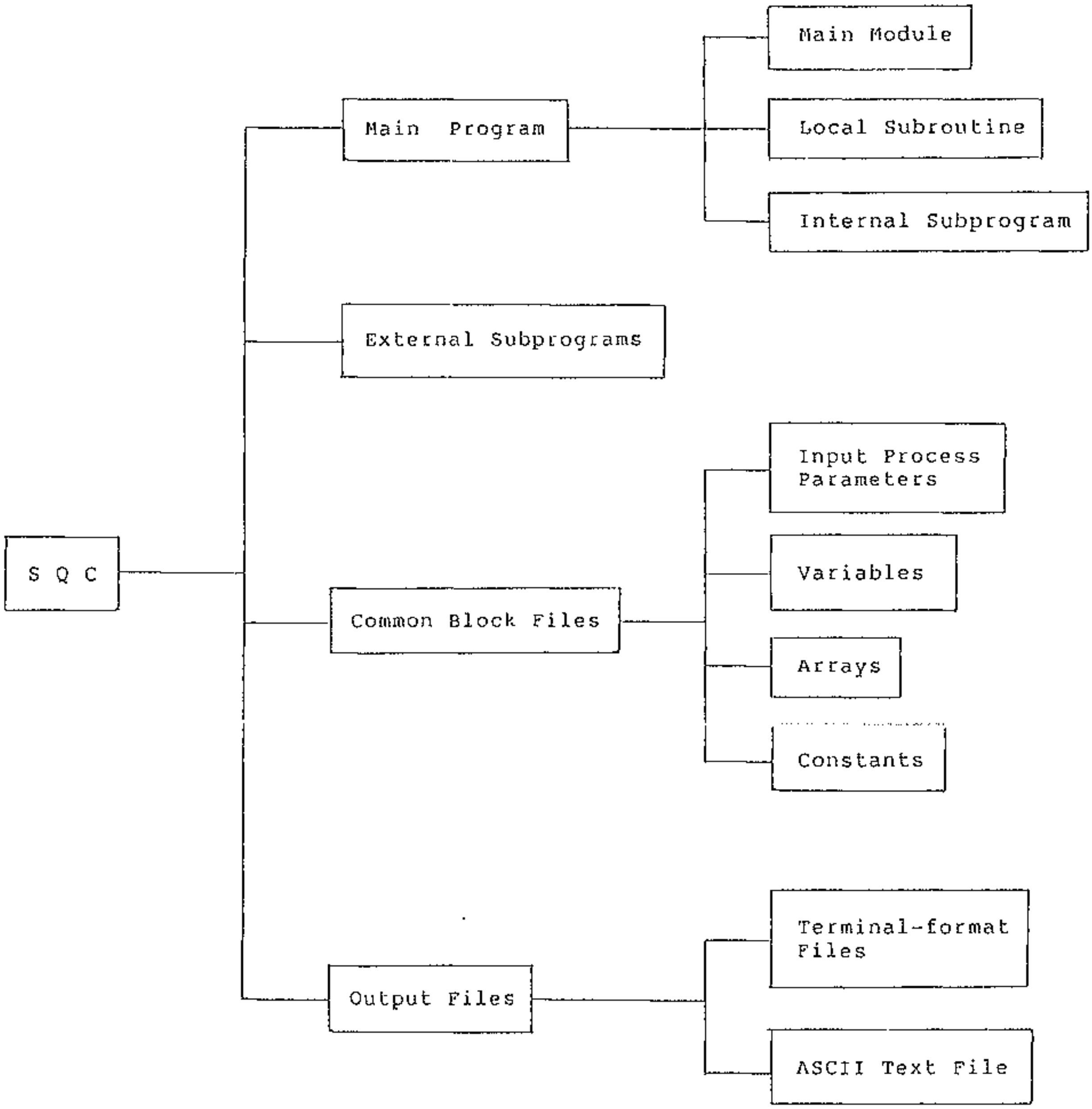


Figure A1.1 SQC program components

1.4 Output files : there are two kinds of output file created by the program :-

1.4.1 Terminal format file : this performs the simple operation of disk file. Sequential access is compulsory in this case. All information of each method requested by users is written onto these files. The outputs appear in the form of statistical reports (see sample reports in Appendix 8). The format of each data field is xxxx.xxxx for floating points and xxxx for integers.

1.4.2 Output file : all produced data in a run will be recorded onto an ASCII text file with sequential organization. However, this file can be accessed indexed-sequentially because record numbers are assigned in the first field of record buffer.

1.5 Input and output field format :

Input field format is free-form format except exponent form, for instance, 1.2e+02 or 3.5e-03 becuase the program will detect all non-numeric data except allowing only one decimal point in each input.

Furthermore, As described in section 1.4.1, the provided output field format is xxxx.xxxx. Hence, any input process parameters that larger than this format must be transformed before so that they can be displayed on the screen.

For example, the average of the bacteria count in waste water is 32,000 /g. It should be transformed to be 32.0 or 320 or 3200 at maximum otherwise the output display on the screen and terminal format file will appear to be and wiil cause other fields shift and will create a new excessive line.

2. Program compilation

Whenever any parts of the program modules are modified (i.e. changed, added, deleted or inserted), the module must be re-compiled by the command

```
$ BASIC <program-name> /[NO]LIST
```

Option /NOLIST is default. /LIST produces a program listing under the file name of <program-name>.LIS where <program-name> can be either main program or external subprogram names. The command BASIC generates an object program or machine-language instructions under the file named <program-name>.OBJ. For example :-

```
$ BASIC SQC /LIST
```

The following output files are generated
SQC.LIS
SQC.OBJ

3. Program linkage

Every time any program modules are modified and re-compiled, "all" module must be linked together by the command

```
$ LINK SQC,CHART_LIMIT,GEN_NORMAL,GEN_POISSON,
GEN_RANDOM,GEN_UNIFORM,HEADING,MIN_MAX,NON_NUMERIC,
OFF_CONTROL,PLOTTING,PLOT_AXIS,PLOT_DATA,READ_MEAN_SD,
READ_METHOD,READ_PARAMETERS,REQUEST,RESULT,RE_ORDER,Z_SCALE
```

<u>Notice</u> : it is rather tedious to type the above command after every time any modules are re-compiled. This can be avoided by set an abbrevated command for it in a LOGIN.COM file as the following instance :-

```
$ LNK_SQC = "LINK SQC,CHART_LIMIT,GEN_NORMAL,GEN_POISSON,
GEN_RANDOM,GEN_UNIFORM,HEADING,MIN_MAX,NON_NUMERIC,
OFF_CONTROL,PLOTTING,PLOT_AXIS,PLOT_DATA,READ_MEAN_SD,
READ_METHOD,READ_PARAMETERS,REQUEST,RESULT,RE_ORDER,Z_SCALE"
```

Hence, whenever it needs to be linked, just type

```
$ LNK_SQC
```

Then only "one" executable image is produced under the name

```
SQC.EXE
```

Therefore, altogether there will be three file types generated :-

```
SQC.BAS,CHART_LIMIT.BAS,GEN_NORMAL, ....BAS, ...etc
SQC.OBJ,CHART_LIMIT.OBJ,GEN_NORMAL, ....OBJ, ...etc
SQC.EXE
```

4. Program running

After all program modules are already compiled and linked, all .OBJ files can be optionally deleted and SQC.EXE is ready to be executed by being invoked by the command :-

```
$ RUN SQC
```

(See "How to run the SQC program" in Chapter 4).

5. Graphic phase implementation

The default graphic area is the square region of the terminal screen (see Figure A1.2). The coordinate system used to specify points in VAX BASIC is a Cartesian system which consists of 2-dimentionals plane referred in the VAX graphics manual as "default drawing board".

The measurement of the length of each axis on the default drawing board is specified on a scale of 0 to 1. This default area can be defined for many viewports for many graphs with different actual scales, which is referred as "transformation", by using the statement

SET VIEWPORT, TRAN #n : xmin, xmax, ymin, ymax .....(A1.1)

where the value n must be between 1 to 255

xmin = minimum of x axis of default drawing board

xmax = maximum of x axis of default drawing board

ymin = minimum of y axis of default drawing board

ymax = maximum of y axis of default drawing board

There are 6 transformations defined in SQC (see Figure A1.3) :

Transformation #1 : for heading and chart details

#2 : for R chart and CuSum chart

#3 : for $\bar{X}$ chart

#4 : for P, C and U chart

#5 : for modified upper CuSum chart

#6 : for modified lower CuSum chart

Note that any graphs plotted beyond the value 0 or 1 of either x or y axis are not displayed on the screen.

However, the actual data are not always lying between 0 and 1 hence those values need to be changed by mapping method using the following window transformation statement :-

SET WINDOW, TRAN #n : xmin, xmax, ymin, ymax .....(A1.2)

where n is the intending transformation of the drawing board
on which the graph is intended to be plotted
xmax = minimum of x axis of actual data
xmin = maximum of x axis of actual data
ymay = minimum of y axis of actual data
ymin = mayimum of y axis of actual data

The VAX GKS provides the graphic capabilities in mapping the values within actual range defined in BASIC statement (A1.2) to the values within abstract range of the drawing board defined in BASIC statement (A1.1).

In establishing a chart in setup phase after each sample is drawn, the whole array of samples, including cumulative control limits calculated from the first sample up to the current sample, will be passed the window transformation mechanism (statement A1.2) hence the scale of each set of samples are changed all the time according to the minimum and maximum values of each set. Furthermore, the frames of transformation windows are designed to have edges whenever the values of input process parameters are much different each run, for example, input process average of the first run is 50 and of the second run is 8.5, This causes the plotted chart to be much diverted from its expected appearance. In order to reduce this scale diversity, before passing the data through statement A1.2, these actual data will be converted into a value between o and 1 by dividing by the absolute value of the maximum magnitude of all samples.

6. Sampling techniques

In 'SAMPLING_ROUTINE', the routine will start with the loop of generating the sampling interval first and then be followed by the loop of sampling simulation. Within both loops the out-of-specification items are checked against the given specifications.

In case of $\bar{X}$-R chart, the normal random variates will be generated while the Poisson variates will be generated for C and U chart. For U chart, the number of inspection units is generated first and the number of defects are generated for each inspection unit according to the number generated. Then the number of defects per inspection unit (u_i) will be calculated.

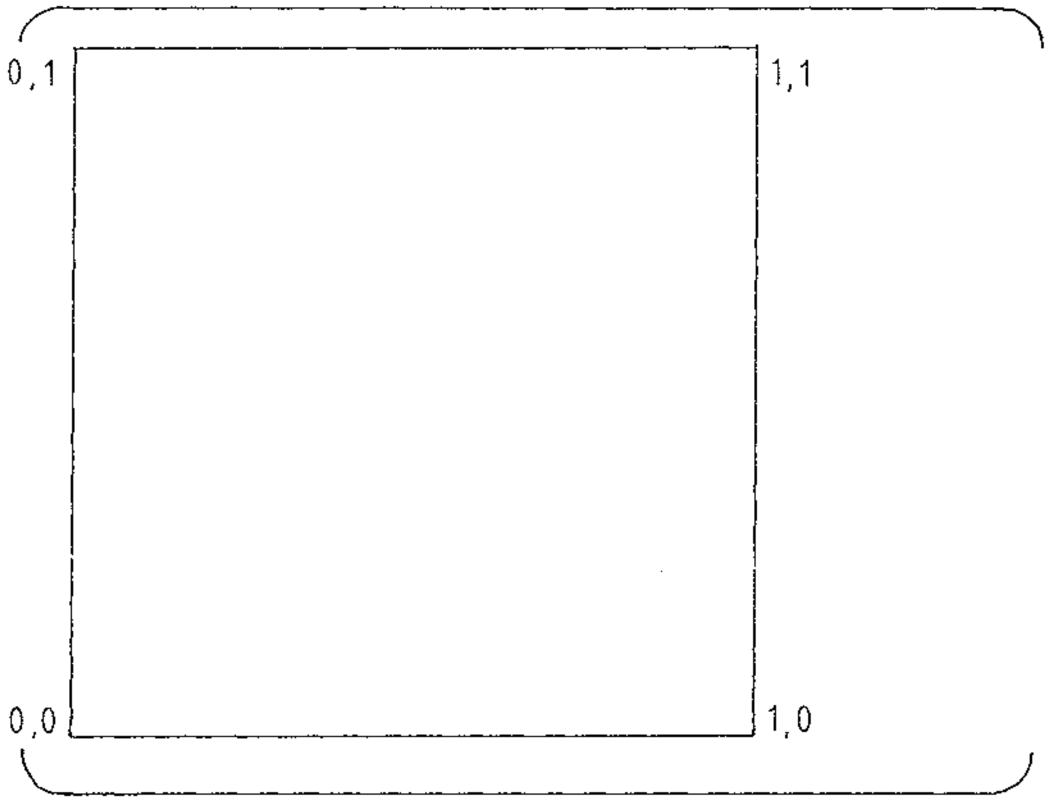
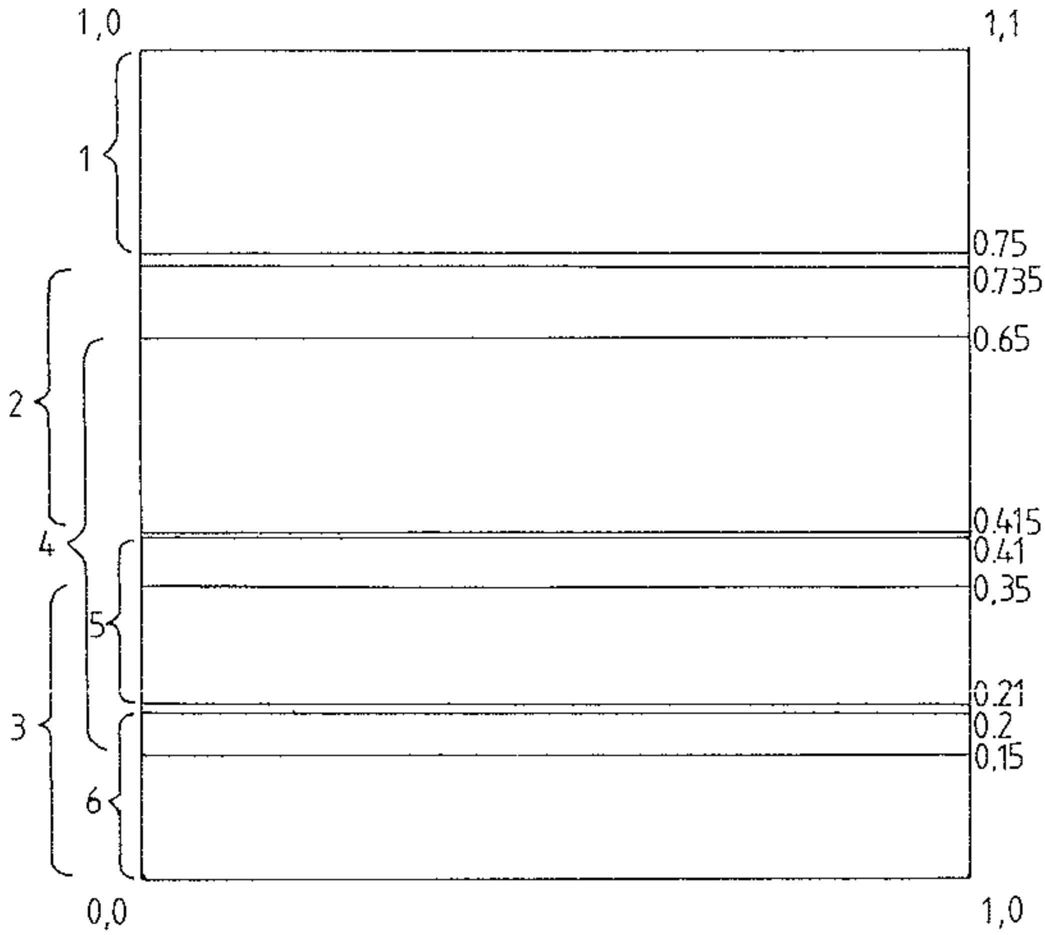


Figure A1.2 Diagram of the default drawing board on the terminal screen



<u>Figure A1.3</u> Diagram shows how the default drawing board is redefined more than one viewports on the screen where :-

transformation #1 : for chart heading
#2 : for R chart and CuSum chart
#3 : for X chart
#4 : for P, C and U chart
#5 : for Upper Modified CuSum chart
#6 : for Lower Modified CuSum chart

Note that the transformation regions were not defined connectedly in order to make the chart appear on the screen at the proper location.

APPENDIX 2

Diagram of SQC Program Structure

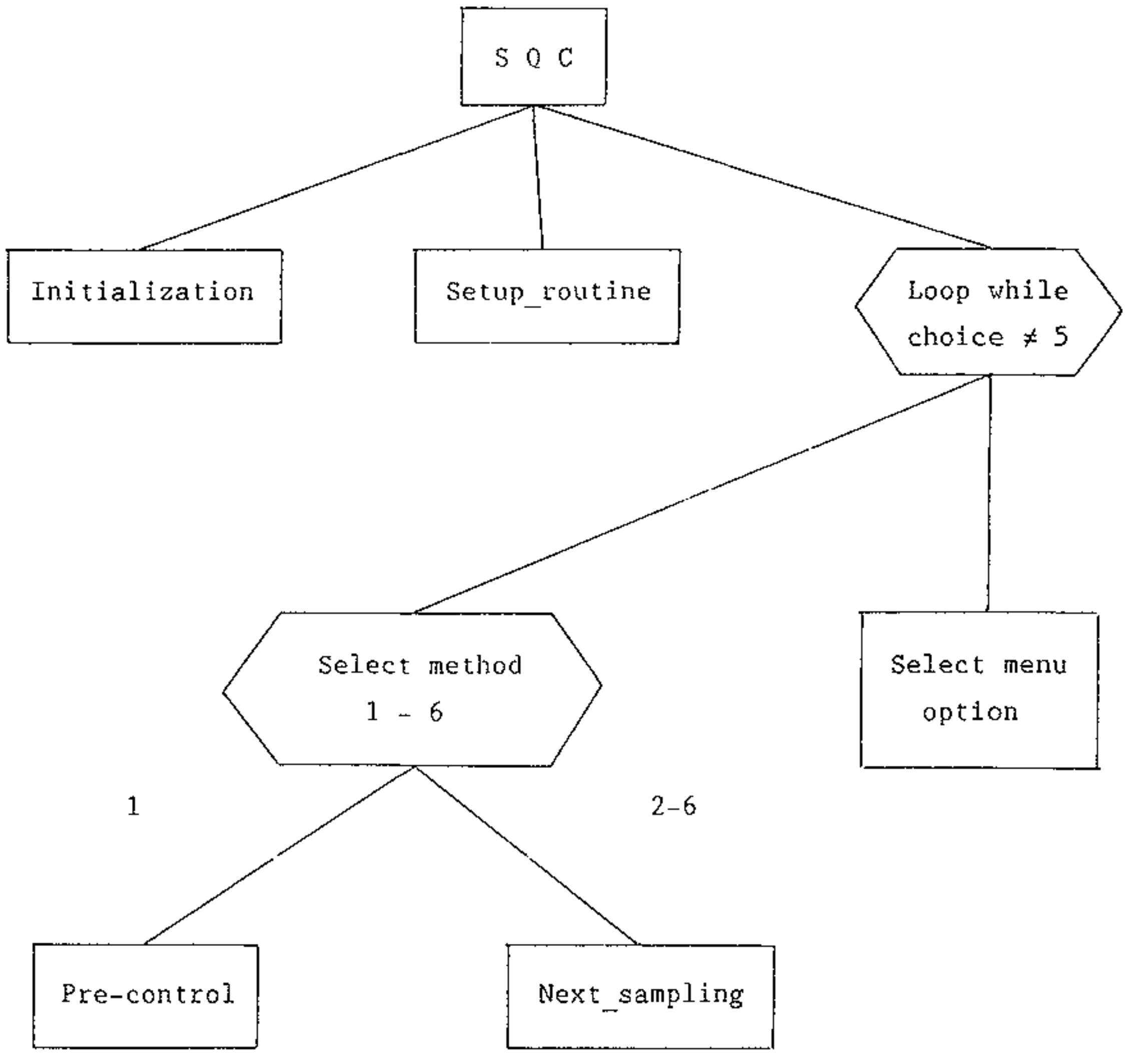


Figure A2.1 Diagram of SQC program structure

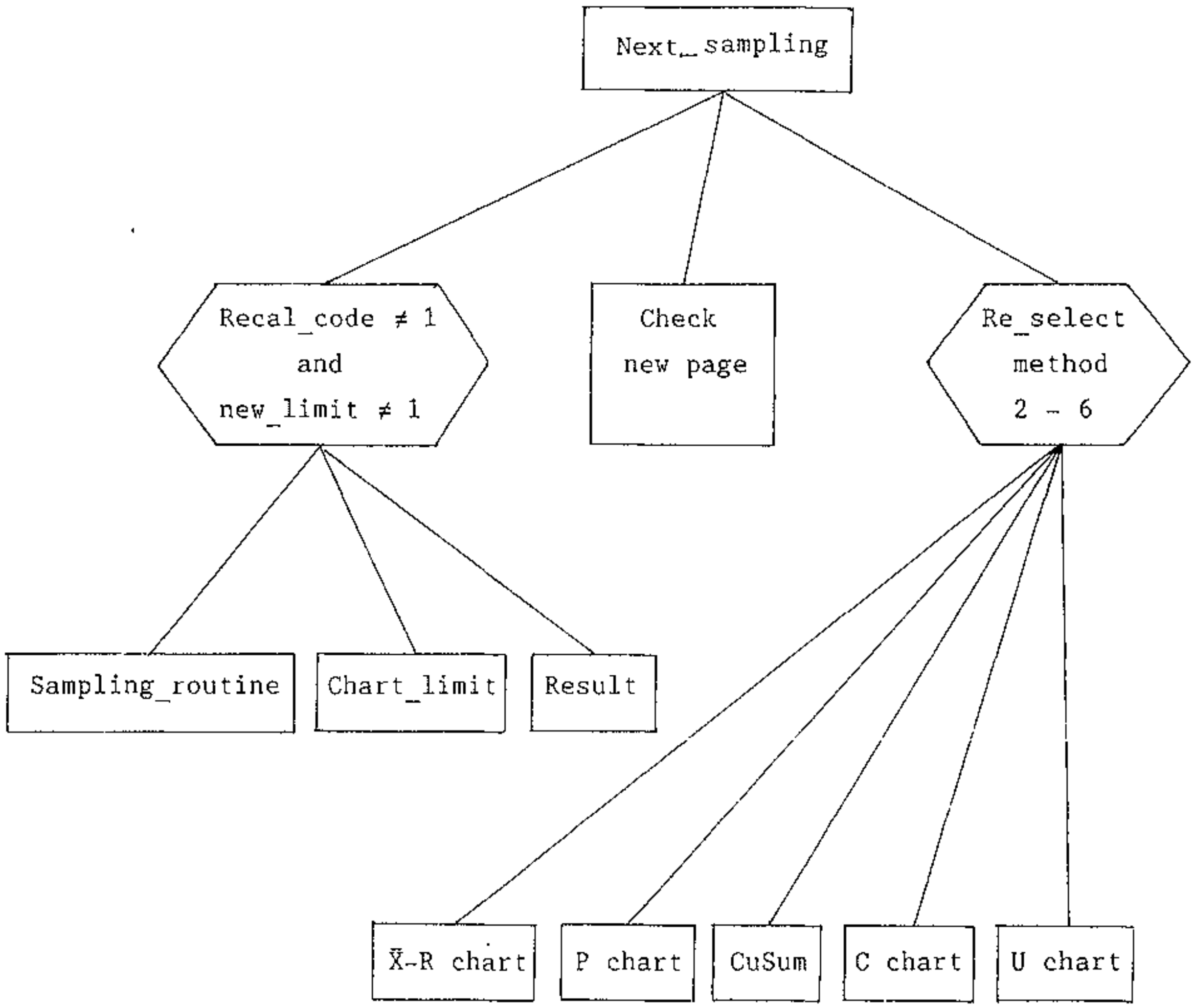


Figure A2.1 Diagram of SQC program structure (cont.)

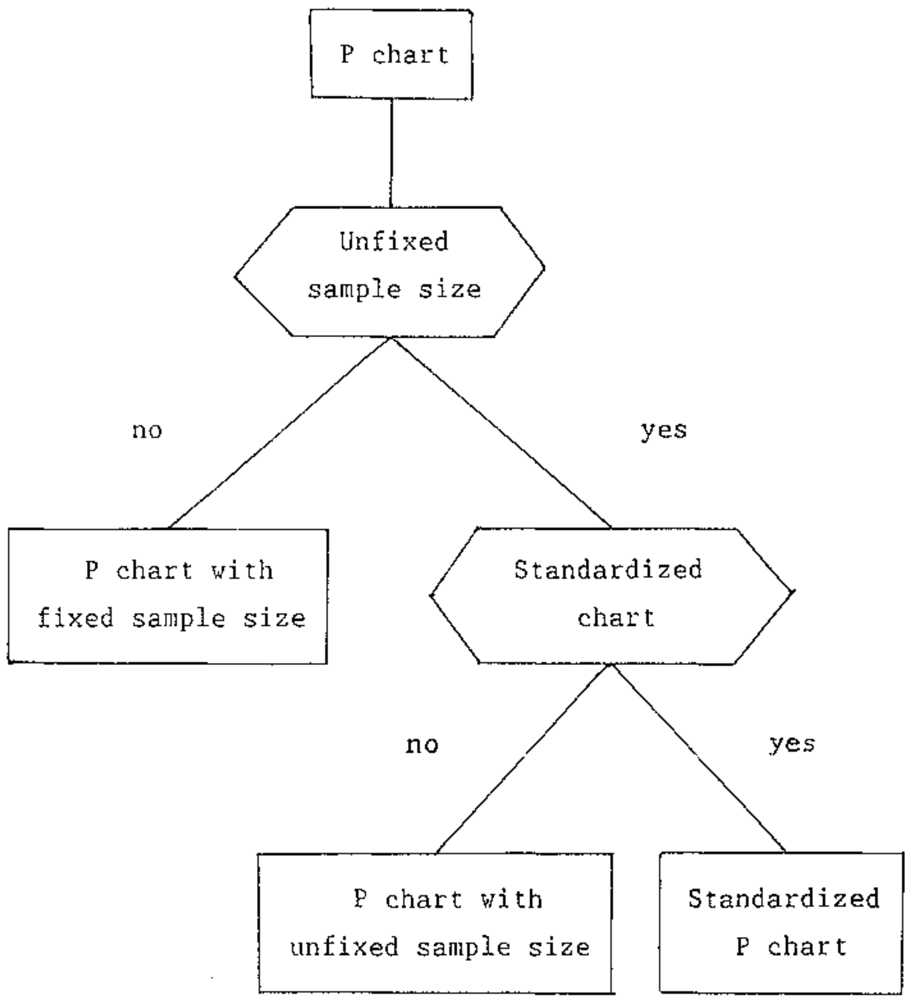


Figure A2.1 Diagram of SQC program structure (cont.)

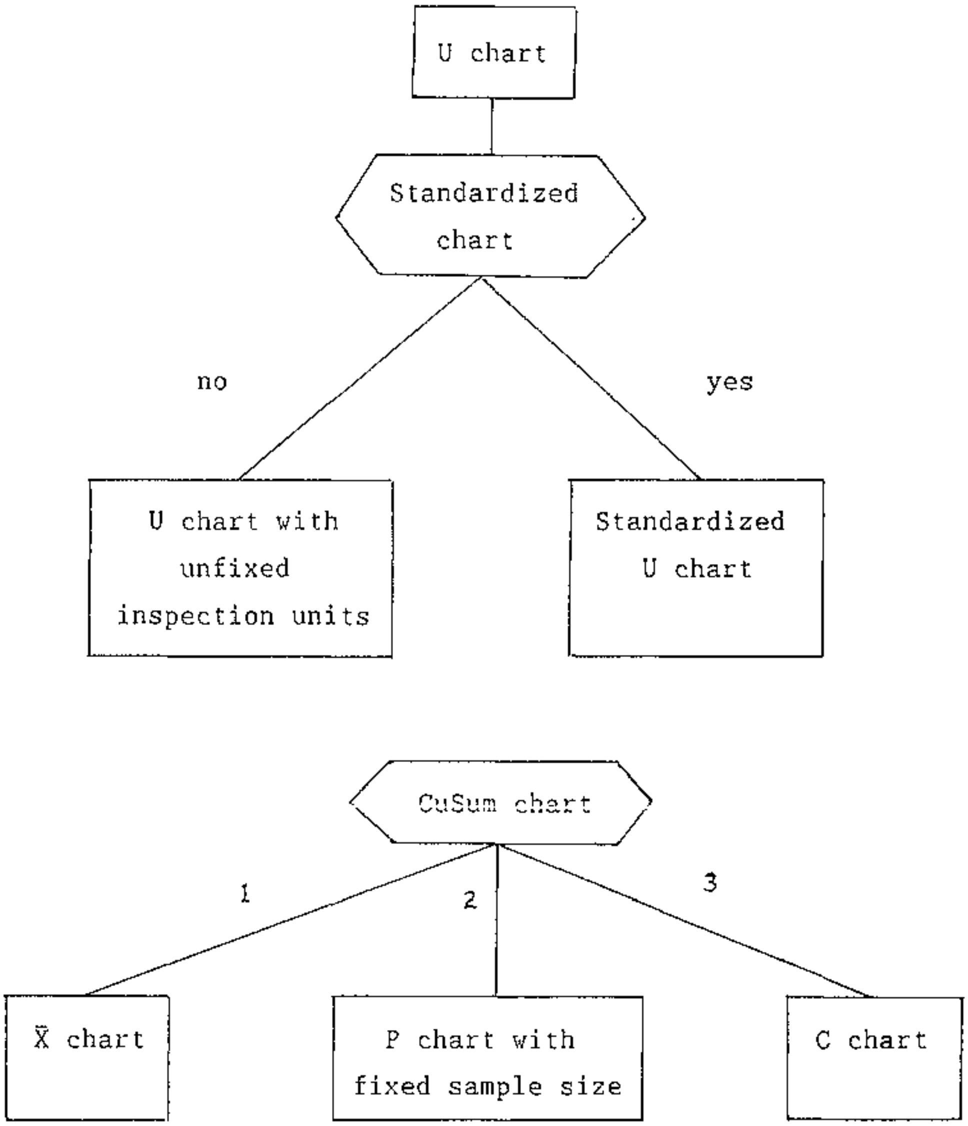


Figure A2.1 Diagram of SQC program structure (cont.)

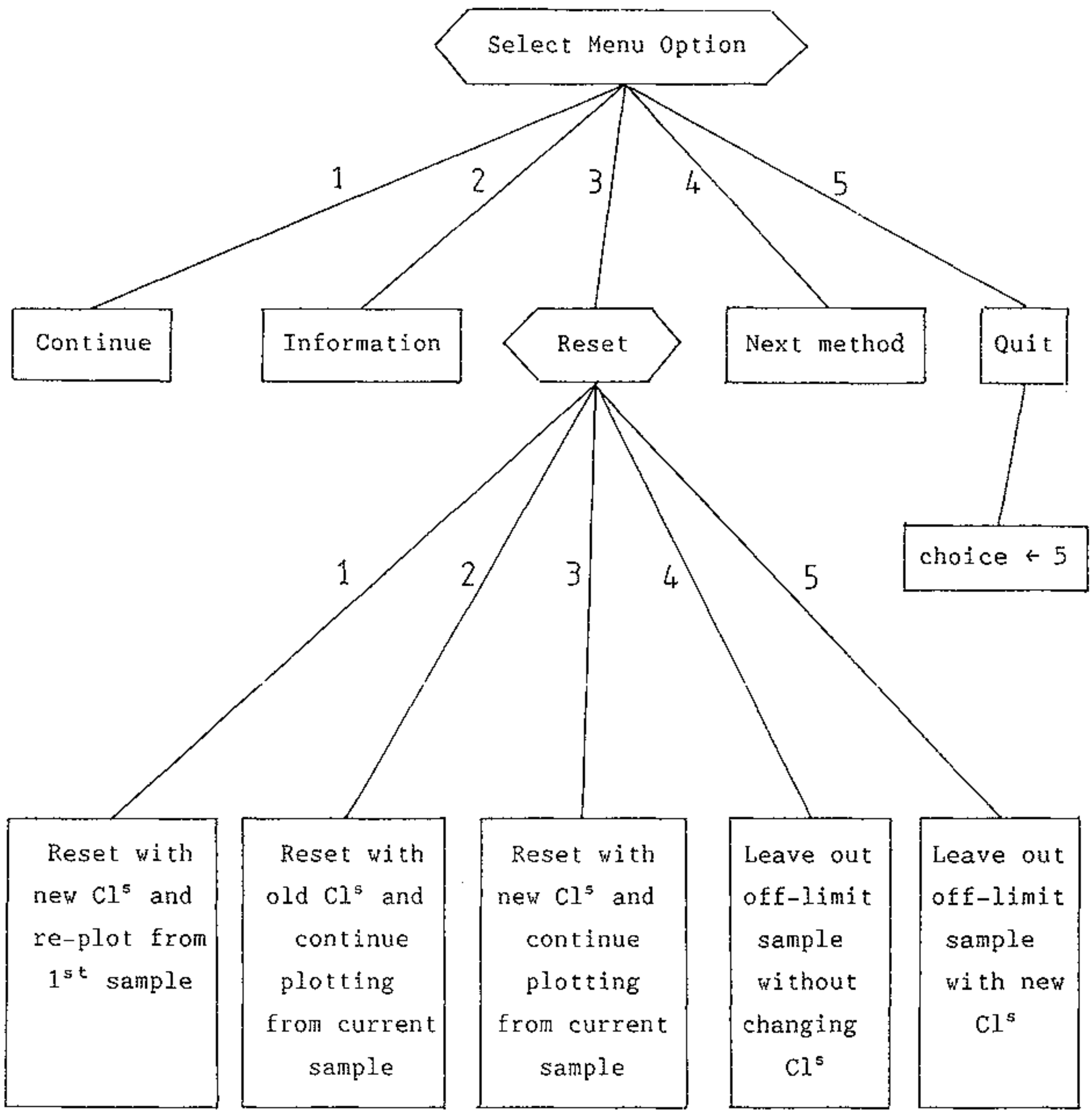


Figure A2.1 Diagram of SQC program structure (cont.)

APPENDIX 3

DATA DESCRIPTION

1. Parameters descriptions

Code	Description	Remarks
seed1	first initial seed	
seed2	second initial seed	> 0 and <= 32767,integer
seed3	third initial seed	
method	selected control method	range from 1 - 6
		1 - Pre-control
		2 - $\bar{X}$-R chart
		3 - CuSum chart
		4 - P chart
		5 - C chart
		6 U chart
sample_no	number of samples	
	for setup phase	> 0 and <= max_sample_no
sampsize	sample size	> 0 and <= max_sampsize
low_range	lower number of variable	
	inspection units	>= 0 and < up_range
up_range	upper number of variable	> low_range and
	inspection units	<= max_sampsize
interval	number of items between	
	samples	> 0 and <= max_interval
lsl	lower specification limit	>= 0 and < usl
usl	upper specification limit	> lsl and <= max_sampsize
A2	control limit factor for	
	$\bar{X}$ chart	
d2	central line factor for	from Appendix IV of
	Range chart	Montgomery(1985)
D3	control limit factor for	
D4	Range chart	

2. Array descriptions

Code	Description
Xbar(1 to 1000)	array for sample averages
Range(1 to 1000)	array for sample ranges
Cusum(1 to 1000)	array for sample cusum
S_plus(1 to 1000)	array for modified upper cusum
S_minus(1 to 1000)	array for modified lower cusum
Samp(1 to 1000)	array for measured variables per sample
Numb(1 to 1000)	array for number of defects per sample
Unit(1 to 1000)	array for number of defects per inspection unit per sample
Cv_y(1 to 1000)	array for converted $\bar{X}$, P and U charts
Cv_y2(1 to 1000)	array for converted R and C chart
Cv_y3(1 to 1000)	array for converted upper modified CuSum
Cv_y4(1 to 1000)	array for converted upper modified CuSum
Item(1 to 1000)	array for bad items from corresponded sample
Off_limit1(1 to 1000)	array for off-limit samples for $\bar{X}$, P, upper CuSum, C and U charts
Off_limit2(1 to 1000)	array for off-limit samples for R and lower CuSum charts
result(1 to 2000,1 to 16)	array for statistical output
	col. 1 : information line counter
	col. 2 : method type
	col. 3 : sample counter after system reset
	col. 4 : sample size
	col. 5 : number of bad items
	col. 6 : percent defectives
	col. 7 : cumulative percent defectives (including sampling interval)

3. Constant descriptions

Code	Description	Remarks*
max_sample_no	maximum number of samples for setup phase	100
max_sampsize	maximum sample size	1000
max_interval	maximum items between samples	10000
full_axis	maximum no. of samples displayed on graphic screen	50
tekoff	text screen setting	
tekon	graphic screen setting	

* program maximum capacity

Array descriptions (cont.)

Code	Description
	col. 8 : $\bar{x}$ or average of no. of defects or average of no. of defects per unit inspection
	col. 9 : range
	col. 10 : process capability ratio
	col. 11 : number of defects in the sample
	col. 12 : lower control limit
	col. 13 : upper control limit
	col. 14 : cumulative number of defects
Factor(1 To 24,1 to 5)	table for factor of control limits
	col. 1 : sample size
	col. 2 : A2 - factor of control limit for $\bar{X}$ chart
	col. 3 : d2 - factor of centre line for range chart
	col. 4 : D3 - factor of control limit for range chart
	col. 5 : D4 - factor of control limit for range chart

4. Common variable descriptions

Code	Description
normal	generated normal variates
m	sample counter
save_m	saved sample counter
pcr	process capability ratio
save_method	saved chart method
big_xbar	average of mean
rbar	average of ranges
pbar	average of fraction non-conforming
cbar	average of no. of non-conformity
ubar	average of no. of non-conformity per unit inspection
x	1st current seed
y	2nd current seed
z	3rd current seed
shoice	selected option for screen menu
line_count	counter for information
tot_bad	total number of bad items
frac	fraction of non-conforming
cumm_bad	cummulative bad items (including between samples)
tot_item	total generated items from normal distribution
h	decision limits for modified cusum
k1	upper reference for modified cusum
k2	lower reference for modified cusum
sigma	standard deviation of process
sigma_sample	population standard deviation
phase	controlling phase and using phase
kount	counter for sample plotting
old_kount	saved kount
starting	starting sample to be plotted on new page
ending	last sample to be plotted on that page

Common variable descriptions (cont.)

Code	Description
off_count1	off-limit sample counter for Xbar, P, C and U charts
off_count2	off-limit sample counter for R chart and lower cusum chart
reset_code	switch for resetting process parameter(s)
recal_code	switch for recalculating new control limits after omitting out-of-control sample(s)
restore_code	switch for restoring all stored information of previous run
delete_code	switch for deleting all previous information stored for displaying
exceed_code	switch to check whether the off-limit sample(s) are within setup number of sample
new_limit	switch for recalculating new control limits
new_page	switch for refresh and plot chart on new page
unfixed	switch for variable sample size
standard	switch for standardized chart
reference	method to which cusum is applied

Note : Some variable names were misspelled intentionally because the correct spelled ones are reserved by the VAX BASIC, for example, COUNT becomes KOUNT or CHOICE becomes SHOICE.

5. Variables for control limits descriptions

Code	Description
Rlcl	lower control limit of range chart
Rucl	upper control limit of range chart
Xlcl	lower control limit of xbar chart
Xucl	upper control limit of xbar chart
Plcl	lower control limit of p chart
Pucl	upper control limit of p chart
Clcl	lower control limit of c chart
Cucl	upper control limit of c chart
V_lcl(1 to 1000)	lower control limit of u chart
v_ucl(1 to 1000)	upper control limit of u chart

6. Variables for savings

Code	Description
Save4_lcl Save4_ucl Save4_centre	saved limits of p chart
Save4_cv_lcl Save4_cv_ucl Save4_cv_centre	saved converted-limits of p chart
Save21_lcl Save21_ucl Save21_centre	saved limits of range chart
Save21_cv_lcl Save21_cv_ucl Save21_cv_centre	saved converted-limits of range chart
Save22_lcl Save22_ucl Save22_centre	saved limits of xbar chart
Save22_cv_lcl Save22_cv_ucl Save22_cv_centre	saved converted-limits of xbar chart
Save31_lcl Save31_ucl Save31_centre	saved limits of upper cusum
Save31_cv_lcl Save31_cv_ucl Save31_cv_centre	saved converted-limits of upper cusum
Save32_lcl Save32_ucl Save32_centre	saved limits of lower cusum
Save32_cv_lcl Save32_cv_ucl Save32_cv_centre	saved converted-limits of lower cusum
yx	absolute value of maximum of items generated
yx2	saved yx used for R, CuSum and C chart
yx3	saved yx used for $\bar{X}$, upper and lower CuSum and U charts

APPENDIX 4

Table of Common Block Files Called by Subprograms

	CONST.BAS	VAR.BAS	SAVE_VAR.BAS	LIMIT.BAS	PARA.BAS	ARRAY.BAS
chart_limit.bas		X	X	X	X	X
gen_normal.bas		X				
gen_poisson.bas		X				
gen_uniform.bas		X				
heading.bas	X	X			X	
off_control.bas		X			X	
plotting.bas	X	X	X		X	X
save_value						
back_save						
plot_axis.bas	X	X	X		X	X
plot_data.bas	X	X	X	X	X	X
read_mean_sd.bas		X			X	
read_method.bas		X			X	
read_parameters.bas	X	X			X	X
tab_search						
message						
result.bas	X	X		X	X	X
re_order.bas		X				
SQC						
init_var	X	X		X		X
information	X	X	X	X	X	X
main_routine		X			X	X
tab_create						X
read_seeds		X			X	
pre_control	X	X		X	X	X
xbar_r_chart		X	X	X	X	X
p_chart		X	X	X	X	X
cusum_chart		X	X	X		X
c_chart		X	X	X	X	X
u_chart		X	X	X	X	X
check_para		X			X	

APPENDIX 5

Table of Parameters Required by Each Chart Method

method	mean	sd	no. of samples	sample size	variable size low_range-up_range	specs
1	X	X				X
2	X	X	X	X		X
4	X	X	X	X		X
4[1]	X	X	X		X	X
5	X		X			
6	X		X		X	
3[2]						

[1] : P chart with variable sample size

[2] : Parameters for CuSum chart depends on control chart it is applied to

APPENDIX 6

Map Block for Record Buffer

field no.	field name	field description	field type
1	rec_no	record number	integer
2	out_method	number of chart method	integer
3	out_reference	number of applied chart in case of CuSum chart	integer
4	out_m	recorded sample number	integer
5	out_sample_no	number of samples in setup phase	integer
6	out_sampsize	sample size	integer
7	out_normal	sample average	real
8	out_defect	number of defects (per unit inspection)	integer
9	out_bad	number of bad items per sample	integer
10	out_cumm_bad	cumulative number of bad items counted from the first sample	integer

APPENDIX 7

List of Program Modules

1. chart_limit.bas
2. gen_normal.bas
3. gen_poisson.bas
4. gen_uniform.bas
5. gen_random.bas
6. heading.bas
7. min_max.bas
8. non_numeric.bas
9. off_control.bas
10. plotting.bas
    - 10.1 save_value
    - 10.2 back_save
11. plot_axis.bas
    - 11.1 vertical_axis
12. plot_data.bas
    - 12.1 phase_1
    - 12.2 phase_2
13. read_mean_sd.bas
14. read_method.bas
    - 14.1 standard_rtn
15. read_parameters.bas
    - 15.1 tab_search
    - 15.2 message
16. request.bas
17. result.bas
18. re_order.bas
19. z_scale.bas
20. SQC*
    - 20.1 local subroutines
        - 20.1.1 initialization
        - 20.1.2 setup_routine
        - 20.1.3 change_para

- 20.1.4 change_seeds
- 20.1.5 re_calculate

20.2 internal subprograms

- 20.2.1 init_var
- 20.2.2 information
  - 20.2.2.1 printing
    - - details
    - - head_form
  - 20.2.2.2 para_detail
  - 20.2.2.3 inform_1
  - 20.2.2.3 inform_2
  - 20.2.2.3 inform_3
  - 20.2.2.3 inform_4
  - 20.2.2.3 inform_5
- 20.2.3 main_routine
- 20.2.4 tab_create
- 20.2.5 read_seeds
- 20.2.6 pre_control
  - 20.2.6.1 draw_line
  - 20.2.6.2 detail
- 20.2.7 xbar_r_chart
- 20.2.8 p_chart
- 20.2.9 cusum_chart
- 20.2.10 c_chart
- 20.2.11 u_chart
- 20.2.12 check_para
  - 20.2.12.1 check_sd
  - 20.2.12.2 check_sample
  - 20.2.12.3 check_size
  - 20.2.12.4 check_interval
  - 20.2.12.5 check_spec

* SQC is the main program.

APPENDIX 8

Examples of information reports

Today's date : 11-Jan-89
Current time : 01:40 PM

Input parameters :
===============
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 30
sd = 1
lower specification = 27
upper specification = 33
sample size = 4
between-sample size = 100

no. of samples	sample size(n)	bad items	P=(x/n)	$\overline{X}$	R	cumm. p
1	4	0	0.0000	30.4049	1.9787	0.0000
2	4	0	0.0000	30.6575	2.8872	0.0000
3	4	0	0.0000	29.5595	1.3496	0.0000
4	4	0	0.0000	30.0112	2.2422	0.0000
5	4	0	0.0000	30.3735	1.7123	0.0000
6	4	0	0.0000	30.1965	1.9575	0.0000
7	4	0	0.0000	30.4740	2.6209	0.0000
8	4	0	0.0000	29.1017	3.4397	0.0000
9	4	0	0.0000	30.4826	1.0058	0.0000
10	4	0	0.0000	29.8005	1.3779	0.0000
11	4	0	0.0000	30.1453	3.3938	0.0009
12	4	0	0.0000	29.8553	1.4846	0.0008
13	4	0	0.0000	30.3162	3.5756	0.0015
14	4	0	0.0000	30.6669	1.4402	0.0014
15	4	0	0.0000	29.7673	3.0931	0.0013
16	4	0	0.0000	29.9255	3.4115	0.0018
17	4	0	0.0000	29.7705	2.8815	0.0017
18	4	0	0.0000	29.4744	2.1274	0.0016
19	4	0	0.0000	30.2949	2.2695	0.0015
20	4	0	0.0000	29.7938	2.8115	0.0019

Current control limits for 20 samples :
Xbar-R Chart :
x(ucl) = 31.769
xbar = 30.0536
x(lcl) = 28.3383

r(ucl) = 5.36959
rbar = 2.35302
r(lcl) = 0

current PCR = .875046

Control limits of the first 20 samples :
x(ucl) = 31.769
xbar = 30.0536
x(lcl) = 28.3383

r(ucl) = 5.36959
rbar = 2.35302
r(lcl) = 0

PCR = .875046

```
Today's date : 11-Jan-89
Current time : 01:43 PM

 Input parameters :
 ================
 Initial seeds :
  - seed1 =  22217
  - seed2 =  2627
  - seed3 =  6307

 number of sample in setup phase =  20
 mean                  =  30.5
 sd                    =  1
 lower specification =  27
 upper specification =  33
 sample size           =  4
 between-sample size =  100
```

no. of samples	sample size(n)	bad items	P=(x/n)	$\bar{X}$	R	cumm. p
1	4	0	0.0000	29.9576	2.0410	0.0096
2	4	0	0.0000	30.5287	1.6086	0.0240
3	4	0	0.0000	30.1503	1.0291	0.0192
4	4	0	0.0000	30.7526	2.1051	0.0192
5	4	0	0.0000	30.0936	1.8103	0.0173
6	4	0	0.0000	30.6941	1.7300	0.0144
7	4	0	0.0000	31.3817	2.0377	0.0124
8	4	0	0.0000	31.5751	2.1148	0.0120
9	4	0	0.0000	30.6893	1.2966	0.0128
10	4	0	0.0000	29.9235	2.4248	0.0115
11	4	0	0.0000	30.9496	2.7703	0.0105
12	4	0	0.0000	30.7146	3.8070	0.0104
13	4	0	0.0000	29.9531	1.6917	0.0096
14	4	0	0.0000	31.0203	4.1899	0.0096
15	4	0	0.0000	31.1496	2.6432	0.0096
16	4	0	0.0000	29.9608	1.8478	0.0108
17	4	0	0.0000	30.7674	2.1587	0.0102
18	4	0	0.0000	30.2071	2.5631	0.0096
19	4	1	0.2500	31.8771	2.5731	0.0096

```
Current control limits for  39  samples :
Xbar-R Chart :
x(ucl) =  32.0171
xbar   =  30.3441
x(lcl) =  28.671

r(ucl) =  5.23709
rbar   =  2.29496
r(lcl) =  0

current PCR    =  .897185

Control limits of the first  20  samples :
x(ucl) =  31.769
xbar   =  30.0536
x(lcl) =  28.3383

r(ucl) =  5.36959
rbar   =  2.35302
r(lcl) =  0

PCR    =  .875046
```

Today's date : 11-Jan-89
Current time : 01:44 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 31
sd = 1
lower specification = 27
upper specification = 33
sample size = 4
between-sample size = 100

no. of samples	sample size(n)	bad items	P=(x/n)	$\overline{X}$	R	cumm. p
1	4	0	0.0000	30.4576	2.0410	0.0288
2	4	0	0.0000	31.0287	1.6086	0.0481
3	4	0	0.0000	30.6503	1.0291	0.0481
4	4	0	0.0000	31.2526	2.1051	0.0457
5	4	0	0.0000	30.5936	1.8103	0.0423
6	4	0	0.0000	31.1941	1.7300	0.0369
7	4	0	0.0000	31.8817	2.0377	0.0330

Current control limits for 27 samples :
Xbar-R Chart :
x(ucl) = 31.9055
xbar = 30.3011
x(lcl) = 28.6967

r(ucl) = 5.02227
rbar = 2.20082
r(lcl) = 0

current PCR = .93556

Control limits of the first 20 samples :
x(ucl) = 31.769
xbar = 30.0536
x(lcl) = 28.3383

r(ucl) = 5.36959
rbar = 2.35302
r(lcl) = 0

PCR = .875046

```
Today's date : 11-Jan-89
Current time : 01:46 PM


 Input parameters :
 ================
 Initial seeds :
  - seed1 =  22217
  - seed2 =  2627
  - seed3 =  6307

 number of sample in setup phase =  20
 mean                 =  31.5
 sd                   =  1
 lower specification =  27
 upper specification =  33
 sample size          =  4
 between-sample size =  100
```

no. of samples	sample size(n)	bad items	P=(x/n)	$\overline{X}$	R	cumm. p
1	4	0	0.0000	30.9576	2.0410	0.0769
2	4	0	0.0000	31.5287	1.6086	0.0817
3	4	0	0.0000	31.1503	1.0291	0.0833
4	4	0	0.0000	31.7526	2.1051	0.0817
5	4	0	0.0000	31.0936	1.8103	0.0788
6	4	0	0.0000	31.6941	1.7300	0.0737
7	4	1	0.2500	32.3817	2.0377	0.0728

```
Current control limits for  27  samples :
Xbar-R Chart :
x(ucl) =  32.0352
xbar   =  30.4308
x(lcl) =  28.8264

r(ucl) =  5.02227
rbar   =  2.20082
r(lcl) =  0

current PCR     =  .93556

Control limits of the first  20  samples :
x(ucl) =  31.769
xbar   =  30.0536
x(lcl) =  28.3383

r(ucl) =  5.36959
rbar   =  2.35302
r(lcl) =  0

PCR     =  .875046
```

Today's date : 11-Jan-89
Current time : 01:47 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 32
sd = 1
lower specification = 27
upper specification = 33
sample size = 4
between-sample size = 100

no. of samples	sample size(n)	bad items	P=(x/n)	$\overline{X}$	R	cumm. p
1	4	0	0.0000	31.4576	2.0410	0.1154
2	4	0	0.0000	32.0287	1.6086	0.1635

Current control limits for 22 samples :
Xbar-R Chart :
x(ucl) = 31.8876
xbar = 30.2072
x(lcl) = 28.5269

r(ucl) = 5.26001
rbar = 2.305
r(lcl) = 0

current PCR = .893276

Control limits of the first 20 samples :
x(ucl) = 31.769
xbar = 30.0536
x(lcl) = 28.3383

r(ucl) = 5.36959
rbar = 2.35302
r(lcl) = 0

PCR = .875046

```
Today's date : 11-Jan-89
Current time : 01:48 PM

 Input parameters :
 ================
 Initial seeds :
  - seed1 =  22217
  - seed2 =  2627
  - seed3 =  6307

 number of sample in setup phase =  20
 mean                  =  32.5
 sd                    =  1
 lower specification =  27
 upper specification =  33
 sample size           =  4
 between-sample size =  100
```

no. of samples	sample size(n)	bad items	P=(x/n)	$\tilde{X}$	R	cumm. p
1	4	0	0.0000	31.9576	2.0410	0.2692

```
Current control limits for  21  samples :
Xbar-R Chart :
x(ucl) =  31.8488
xbar   =  30.1443
x(lcl) =  28.4398

r(ucl) =  5.33568
rbar   =  2.33816
r(lcl) =  0

current PCR     =  .880606

Control limits of the first  20  samples :
x(ucl) =  31.769
xbar   =  30.0536
x(lcl) =  28.3383

r(ucl) =  5.36959
rbar   =  2.35302
r(lcl) =  0

PCR    =  .875046
```

Today's date : 11-Jan-89
Current time : 01:49 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 30
sd = 1
lower specification = 27
upper specification = 33
sample size = 4
between-sample size = 100

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	30.4049	0.3513	0.0656	0.0000	0.0000
2	30.6575	0.9553	0.3839	0.0000	0.0000
3	29.5595	0.4611	0.0000	-0.2084	0.0000
4	30.0112	0.4187	0.0000	0.0000	0.0000
5	30.3735	0.7386	0.0342	0.0000	0.0000
6	30.1965	0.8815	0.0000	0.0000	0.0000
7	30.4740	1.3019	0.1347	0.0000	0.0000
8	29.1017	0.3500	0.0000	-0.6662	0.0000
9	30.4826	0.7790	0.1433	0.0000	0.0000
10	29.8005	0.5259	0.0000	0.0000	0.0000
11	30.1453	0.6176	0.0000	0.0000	0.0009
12	29.8553	0.4193	0.0000	0.0000	0.0008
13	30.3162	0.6819	0.0000	0.0000	0.0015
14	30.6669	1.2952	0.3276	0.0000	0.0014
15	29.7673	1.0088	0.0000	-0.0006	0.0013
16	29.9255	0.8807	0.0000	0.0000	0.0018
17	29.7705	0.5976	0.0000	0.0000	0.0017
18	29.4744	0.0184	0.0000	-0.2935	0.0016
19	30.2949	0.2597	0.0000	0.0000	0.0015
20	29.7938	-0.0001	0.0000	0.0000	0.0019

Current control limits for 20 samples :
Cusum Chart for : (Xbar-R Chart)
Upper decision interval = 2.85699
Upper Reference value = 30.3393
Reference value = 30.0536
Lower Reference value = 29.7679
Lower decision interval = -2.85699

Today's date : 11-Jan-89
Current time : 01:49 PM

Input parameters :
===============
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 30.5
sd = 1
lower specification = 27
upper specification = 33
sample size = 4
between-sample size = 100

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	29.9576	-0.0915	0.0000	0.0000	0.0096
2	30.5287	0.3664	0.1894	0.0000	0.0240
3	30.1503	0.4424	0.0005	0.0000	0.0192
4	30.7526	1.0924	0.4137	0.0000	0.0192
5	30.0936	1.0838	0.1679	0.0000	0.0173
6	30.6941	1.6529	0.5228	0.0000	0.0144
7	31.3817	2.8631	1.5651	0.0000	0.0124
8	31.5751	4.2165	2.8009	0.0000	0.0120
9	30.6893	4.6681	3.1509	0.0000	0.0128

Current control limits for 29 samples :
Cusum Chart for : (Xbar-R Chart)
Upper decision interval = 2.85699
Upper Reference value = 30.3393
Reference value = 30.0536
Lower Reference value = 29.7679
Lower decision interval = -2.85699

Today's date : 11-Jan-89
Current time : 01:50 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 31
sd = 1
lower specification = 27
upper specification = 33
sample size = 4
between-sample size = 100

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	30.4576	0.3847	0.1183	0.0000	0.0288
2	31.0287	1.2971	0.8077	0.0000	0.0481
3	30.6503	1.8080	1.1188	0.0000	0.0481
4	31.2526	2.8746	2.0320	0.0000	0.0457
5	30.5936	3.2660	2.2863	0.0000	0.0423
6	31.1941	4.2197	3.1411	0.0000	0.0369

Current control limits for 26 samples :
Cusum Chart for : (Xbar-R Chart)
Upper decision interval = 2.85699
Upper Reference value = 30.3393
Reference value = 30.0536
Lower Reference value = 29.7679
Lower decision interval = -2.85699

Today's date : 11-Jan-89
Current time : 01:52 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 31.5
sd = 1
lower specification = 27
upper specification = 33
sample size = 4
between-sample size = 100

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	30.9576	0.8609	0.6183	0.0000	0.0769
2	31.5287	2.2279	1.8077	0.0000	0.0817
3	31.1503	3.1735	2.6188	0.0000	0.0833
4	31.7526	4.6568	4.0320	0.0000	0.0817

Current control limits for 24 samples :
Cusum Chart for : (Xbar-R Chart)
Upper decision interval = 2.85699
Upper Reference value = 30.3393
Reference value = 30.0536
Lower Reference value = 29.7679
Lower decision interval = -2.85699

Today's date : 11-Jan-89
Current time : 01:53 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 32
sd = 1
lower specification = 27
upper specification = 33
sample size = 4
between-sample size = 100

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	31.4576	1.3371	1.1183	0.0000	0.1154
2	32.0287	3.1586	2.8077	0.0000	0.1635
3	31.6503	4.5390	4.1188	0.0000	0.1635

Current control limits for 23 samples :
Cusum Chart for : (Xbar-R Chart)
Upper decision interval = 2.85699
Upper Reference value = 30.3393
Reference value = 30.0536
Lower Reference value = 29.7679
Lower decision interval = -2.85699

Today's date : 11-Jan-89
Current time : 01:54 PM

Input parameters :
===============
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 32.5
sd = 1
lower specification = 27
upper specification = 33
sample size = 4
between-sample size = 100

no. of samples	refer-chart value	cusum	S+	S−	cumm. bad
1	31.9576	1.8133	1.6183	0.0000	0.2692
2	32.5287	4.0893	3.8077	0.0000	0.3269

Current control limits for 22 samples :
Cusum Chart for : (Xbar-R Chart)
Upper decision interval = 2.85699
Upper Reference value = 30.3393
Reference value = 30.0536
Lower Reference value = 29.7679
Lower decision interval = -2.85699

Today's date : 11-Jan-89
Current time : 01:55 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 30
sd = 1
lower specification = 27
upper specification = 33
sample size = 40
between-sample size = 100

no. of samples	sample size(n)	bad items	P=(x/n)	$\overline{X}$	R	cumm. p
1	40	0	0.0000	30.0231	4.6585	0.0000
2	40	0	0.0000	30.0094	5.2186	0.0000
3	40	0	0.0000	29.9191	3.9127	0.0000
4	40	0	0.0000	29.9984	5.5962	0.0000
5	40	0	0.0000	30.0753	4.0586	0.0000
6	40	0	0.0000	30.2869	5.3056	0.0000
7	40	0	0.0000	30.0620	3.5247	0.0000
8	40	0	0.0000	29.8318	3.4217	0.0009
9	40	0	0.0000	29.8066	4.7832	0.0008
10	40	0	0.0000	30.0557	5.3565	0.0014
11	40	0	0.0000	29.8466	4.1153	0.0013
12	40	1	0.0250	29.8738	6.0236	0.0018
13	40	0	0.0000	30.1454	4.3090	0.0016
14	40	0	0.0000	30.0592	4.9297	0.0015
15	40	0	0.0000	29.9355	4.7853	0.0019
16	40	0	0.0000	30.0662	4.4516	0.0018
17	40	1	0.0250	30.1697	4.9434	0.0029
18	40	0	0.0000	30.1926	5.2149	0.0028
19	40	0	0.0000	30.0283	4.7320	0.0026
20	40	0	0.0000	29.9383	4.1794	0.0029

Current control limits for 20 samples :
P Chart :
p(ucl) = .261874E-01
pbar = .0025
p(lcl) = 0

Control limits of the first 20 samples :
p(ucl) = .261874E-01
pbar = .0025
p(lcl) = 0

Today's date : 11-Jan-89
Current time : 01:56 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 30.5
sd = 1
lower specification = 27
upper specification = 33
sample size = 40
between-sample size = 100

no. of samples	sample size(n)	bad items	P=(x/n)	$\overline{X}$	R	cumm. p
1	40	0	0.0000	30.6032	3.8306	0.0071
2	40	0	0.0000	30.3604	4.2903	0.0107
3	40	0	0.0000	30.5944	3.7055	0.0071
4	40	0	0.0000	30.7545	4.3726	0.0071
5	40	1	0.0250	30.6179	5.2777	0.0071
6	40	0	0.0000	30.2969	4.3177	0.0071
7	40	0	0.0000	30.4497	4.3154	0.0092
8	40	0	0.0000	30.6631	4.2486	0.0080
9	40	1	0.0250	30.4012	4.9951	0.0079
10	40	0	0.0000	30.5740	3.9070	0.0071
11	40	0	0.0000	30.5197	4.5612	0.0065
12	40	0	0.0000	30.5564	5.1063	0.0065
13	40	0	0.0000	30.6342	4.5259	0.0066
14	40	0	0.0000	30.2387	3.6328	0.0061
15	40	0	0.0000	30.2461	5.5957	0.0062
16	40	0	0.0000	30.3661	4.4597	0.0063
17	40	1	0.0250	30.4484	5.6404	0.0063
18	40	0	0.0000	30.8655	4.1656	0.0067
19	40	0	0.0000	30.5753	3.6528	0.0064
20	40	0	0.0000	30.7053	4.3955	0.0064
21	40	0	0.0000	30.3705	3.5548	0.0068
22	40	0	0.0000	30.4484	4.8610	0.0068
23	40	0	0.0000	30.2311	4.2774	0.0065
24	40	0	0.0000	30.8170	3.6288	0.0065
25	40	0	0.0000	30.3085	3.5903	0.0063
26	40	0	0.0000	30.7321	4.0458	0.0060
27	40	1	0.0250	30.6054	5.2690	0.0063
28	40	1	0.0250	30.3301	5.2263	0.0066
29	40	0	0.0000	30.4434	4.1458	0.0069
30	40	0	0.0000	30.5965	4.4281	0.0069
31	40	0	0.0000	30.6558	4.4799	0.0067
32	40	0	0.0000	30.4588	4.4829	0.0069
33	40	0	0.0000	30.5019	5.2768	0.0067
34	40	0	0.0000	30.4726	4.3365	0.0065
35	40	2	0.0500	30.6693	5.1329	0.0069

Current control limits for 55 samples :
P Chart :
p(ucl) = .343678E-01
pbar = .409091E-02
p(lcl) = 0

Control limits of the first 20 sam les :

p(ucl) = .261874E-01
pbar = .0025
p(lcl) = 0

Today's date : 11-Jan-89
Current time : 01:57 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 31
sd = 1
lower specification = 27
upper specification = 33
sample size = 40
between-sample size = 100

no. of samples	sample size(n)	bad items	P=(x/n)	$\overline{X}$	R	cumm. p
1	40	2	0.0500	31.1032	3.8306	0.0357

Current control limits for 21 samples :
P Chart :
p(ucl) = .374166E-01
pbar = .47619E-02
p(lcl) = 0

Control limits of the first 20 samples :
p(ucl) = .261874E-01
pbar = .0025
p(lcl) = 0

Today's date : 11-Jan-89
Current time : 01:58 PM

Input parameters :
================

Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 31.5
sd = 1
lower specification = 27
upper specification = 33
sample size = 40
between-sample size = 100

no. of samples	sample size(n)	bad items	P=(x/n)	$\overline{X}$	R	cumm. p
1	40	5	0.1250	31.6032	3.8306	0.0857

Current control limits for 21 samples :
P Chart :
p(ucl) = .514538E-01
pbar = .833333E-02
p(lcl) = 0

Control limits of the first 20 samples :
p(ucl) = .261874E-01
pbar = .0025
p(lcl) = 0

```
Today's date : 11-Jan-89
Current time : 01:59 PM

 Input parameters :
 ================
 Initial seeds :
  - seed1 =  22217
  - seed2 =  2627
  - seed3 =  6307

 number of sample in setup phase =  20
 mean                  =  32
 sd                    =  1
 lower specification =  27
 upper specification =  33
 sample size           =  40
 between-sample size =  100
```

no. of samples	sample size(n)	bad items	P=(x/n)	$\bar{X}$	R	cumm. p
1	40	6	0.1500	32.1032	3.8306	0.1929

```
Current control limits for  21  samples :
P Chart :
p(ucl) =  .555939E-01
pbar   =  .952381E-02
p(lcl) =  0

Control limits of the first  20  samples :
p(ucl) =  .261874E-01
pbar   =  .0025
p(lcl) =  0
```

```
Today's date : 11-Jan-89
Current time : 02:00 PM

 Input parameters :
 ================
 Initial seeds :
  - seed1 =  22217
  - seed2 =  2627
  - seed3 =  6307

 number of sample in setup phase =  20
 mean                   =  32.5
 sd                     =  1
 lower specification =  27
 upper specification =  33
 sample size            =  40
 between-sample size =  100
```

no. of samples	sample size(n)	bad items	P=(x/n)	$\bar{X}$	R	cumm. p
1	40	15	0.3750	32.6032	3.8306	0.3786

```
Current control limits for  21  samples :
P Chart :
p(ucl) =  .870319E-01
pbar   =  .202381E-01
p(lcl) =  0

Control limits of the first  20  samples :
p(ucl) =  .261874E-01
pbar   =  .0025
p(lcl) =  0
```

```
Today's date : 11-Jan-89
Current time : 02:01 PM

 Input parameters :
 ================
 Initial seeds :
  - seed1 =  22217
  - seed2 =  2627
  - seed3 =  6307

 number of sample in setup phase =  20
 mean                  =  30
 sd                    =  1
 lower specification =  27
 upper specification =  33
 sample size           =  40
 between-sample size =  100
```

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	0.0000	-0.0025	0.0000	0.0000	0.0000
2	0.0000	-0.0050	0.0000	0.0000	0.0000
3	0.0000	-0.0075	0.0000	0.0000	0.0000
4	0.0000	-0.0100	0.0000	0.0000	0.0000
5	0.0000	-0.0125	0.0000	0.0000	0.0000
6	0.0000	-0.0150	0.0000	0.0000	0.0000
7	0.0000	-0.0175	0.0000	0.0000	0.0000
8	0.0000	-0.0200	0.0000	0.0000	0.0009
9	0.0000	-0.0225	0.0000	0.0000	0.0008
10	0.0000	-0.0250	0.0000	0.0000	0.0014
11	0.0000	-0.0275	0.0000	0.0000	0.0013
12	0.0250	-0.0050	0.0186	0.0000	0.0018
13	0.0000	-0.0075	0.0121	0.0000	0.0016
14	0.0000	-0.0100	0.0057	0.0000	0.0015
15	0.0000	-0.0125	0.0000	0.0000	0.0019
16	0.0000	-0.0150	0.0000	0.0000	0.0018
17	0.0250	0.0075	0.0186	0.0000	0.0029
18	0.0000	0.0050	0.0121	0.0000	0.0028
19	0.0000	0.0025	0.0057	0.0000	0.0026
20	0.0000	0.0000	0.0000	0.0000	0.0029

```
Current control limits for  20  samples :
Cusum Chart for : (P Chart)
Upper decision interval =  .039479
Upper Reference value   =  .64479E-02
      Reference value   =  .0025
Lower Reference value   = -.14479E-02
Lower decision interval = -.039479
```

Today's date : 11-Jan-89
Current time : 02:02 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 30.5
sd = 1
lower specification = 27
upper specification = 33
sample size = 40
between-sample size = 100

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	0.0000	-0.0024	0.0000	0.0000	0.0071
2	0.0000	-0.0047	0.0000	0.0000	0.0107
3	0.0000	-0.0068	0.0000	0.0000	0.0071
4	0.0000	-0.0089	0.0000	0.0000	0.0071
5	0.0250	0.0131	0.0186	0.0000	0.0071
6	0.0000	0.0102	0.0121	0.0000	0.0071
7	0.0000	0.0074	0.0057	0.0000	0.0092
8	0.0000	0.0047	0.0000	0.0000	0.0080
9	0.0250	0.0263	0.0186	0.0000	0.0079
10	0.0000	0.0230	0.0121	0.0000	0.0071
11	0.0000	0.0197	0.0057	0.0000	0.0065
12	0.0000	0.0166	0.0000	0.0000	0.0065
13	0.0000	0.0136	0.0000	0.0000	0.0066
14	0.0000	0.0106	0.0000	0.0000	0.0061
15	0.0000	0.0078	0.0000	0.0000	0.0062
16	0.0000	0.0050	0.0000	0.0000	0.0063
17	0.0250	0.0266	0.0186	0.0000	0.0063
18	0.0000	0.0233	0.0121	0.0000	0.0067
19	0.0000	0.0201	0.0057	0.0000	0.0064
20	0.0000	0.0170	0.0000	0.0000	0.0064
21	0.0000	0.0140	0.0000	0.0000	0.0068
22	0.0000	0.0110	0.0000	0.0000	0.0068
23	0.0000	0.0081	0.0000	0.0000	0.0065
24	0.0000	0.0052	0.0000	0.0000	0.0065
25	0.0000	0.0025	0.0000	0.0000	0.0063
26	0.0000	-0.0003	0.0000	0.0000	0.0060
27	0.0250	0.0216	0.0186	0.0000	0.0063
28	0.0250	0.0429	0.0371	0.0000	0.0066
29	0.0000	0.0393	0.0307	0.0000	0.0069
30	0.0000	0.0358	0.0242	0.0000	0.0069
31	0.0000	0.0324	0.0178	0.0000	0.0067
32	0.0000	0.0290	0.0113	0.0000	0.0069
33	0.0000	0.0257	0.0049	0.0000	0.0067
34	0.0000	0.0225	0.0000	0.0000	0.0065
35	0.0500	0.0684	0.0436	0.0000	0.0069

Current control limits for 55 samples :
Cusum Chart for : (P Chart)
Upper decision interval = .039479
Upper Reference value = .64479E-02
Reference value = .0025
Lower Reference value = -.14479E-02
Lower decision interval = -.039479

Today's date : 11-Jan-89
Current time : 02:03 PM

Input parameters :
================
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 31
sd = 1
lower specification = 27
upper specification = 33
sample size = 40
between-sample size = 100

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	0.0500	0.0452	0.0436	0.0000	0.0357

Current control limits for 21 samples :
Cusum Chart for : (P Chart)
Upper decision interval = .039479
Upper Reference value = .64479E-02
Reference value = .0025
Lower Reference value = -.14479E-02
Lower decision interval = -.039479

```
Today's date : 11-Jan-89
Current time : 02:04 PM

 Input parameters :
 ================
 Initial seeds :
  - seed1 =  22217
  - seed2 =  2627
  - seed3 =  6307

 number of sample in setup phase =  20
 mean                  =  31.5
 sd                    =  1
 lower specification =  27
 upper specification =  33
 sample size           =  40
 between-sample size =  100
```

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	0.1250	0.1167	0.1186	0.0000	0.0857

```
Current control limits for  21  samples :
Cusum Chart for : (P Chart)
Upper decision interval =  .039479
Upper Reference value   =  .64479E-02
      Reference value   =  .0025
Lower Reference value   = -.14479E-02
Lower decision interval = -.039479
```

```
Today's date : 11-Jan-89
Current time : 02:05 PM

 Input parameters :
 ================
 Initial seeds :
  - seed1 =  22217
  - seed2 =  2627
  - seed3 =  6307

 number of sample in setup phase =  20
 mean                  =  32
 sd                    =  1
 lower specification =  27
 upper specification =  33
 sample size           =  40
 between-sample size =  100
```

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	0.1500	0.1405	0.1436	0.0000	0.1929

```
Current control limits for  21  samples :
Cusum Chart for : (P Chart)
Upper decision interval =  .039479
Upper Reference value   =  .64479E-02
      Reference value   =  .0025
Lower Reference value   = -.14479E-02
Lower decision interval = -.039479
```

Today's date : 11-Jan-89
Current time : 02:06 PM

Input parameters :
===============
Initial seeds :
- seed1 = 22217
- seed2 = 2627
- seed3 = 6307

number of sample in setup phase = 20
mean = 32.5
sd = 1
lower specification = 27
upper specification = 33
sample size = 40
between-sample size = 100

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	0.3750	0.3548	0.3686	0.0000	0.3786

Current control limits for 21 samples :
Cusum Chart for : (P Chart)
Upper decision interval = .039479
Upper Reference value = .64479E-02
Reference value = .0025
Lower Reference value = -.14479E-02
Lower decision interval = -.039479

Today's date : 17-Dec-88
Current time : 02:49 PM

Input parameters :
===============
Initial seeds :
- seed1 = 2
- seed2 = 333
- seed3 = 56

mean = 30
sd = 1
lower specification = 27
upper specification = 33
lower pre-control limit = 28.5
upper pre-control limit = 31.5

no. of item	sampling item	cumm. %defective	cumm. bad item
1	30.3497	0.0000	0
2	28.7677	0.0000	0
3	31.9980	0.0000	0
4	29.4474	0.0000	0
5	29.1447	0.0000	0
6	29.3379	0.0000	0
7	28.8723	0.0000	0
8	29.6371	0.0000	0
9	31.4355	0.0000	0
10	30.9407	0.0000	0
11	28.9000	0.0000	0
12	29.8440	0.0000	0
13	29.6849	0.0000	0
14	30.6190	0.0000	0
15	29.5416	0.0000	0

Today's date : 17-Dec-88
Current time : 02:55 PM

Input parameters :
===============
Initial seeds :
- seed1 = 2
- seed2 = 333
- seed3 = 56

number of sample in setup phase = 10
mean = 31
sd = 1
lower specification = 27
upper specification = 33
variable sample size :
- lower range = 40
- upper range = 60

no. of samples	sample size(n)	bad total	P=(x/n)	lower limit	upper limit	cumm. p
1	40	0	0.0000	0.0000	0.0000	0.0111
2	47	2	0.0426	0.0000	0.0844	0.0214
3	48	2	0.0417	0.0000	0.0996	0.0246
4	52	0	0.0000	0.0000	0.0808	0.0233
5	42	1	0.0238	0.0000	0.0889	0.0230
6	55	2	0.0364	0.0000	0.0861	0.0240
7	51	1	0.0196	0.0000	0.0870	0.0219
8	48	2	0.0417	0.0000	0.0942	0.0255
9	49	2	0.0408	0.0000	0.0973	0.0261
10	41	3	0.0732	0.0000	0.1144	0.0277
11	59	0	0.0000	0.0000	0.0947	0.0277
12	47	0	0.0000	0.0000	0.0971	0.0263
13	49	0	0.0000	0.0000	0.0910	0.0250
14	47	0	0.0000	0.0000	0.0882	0.0233
15	41	3	0.0732	0.0000	0.1010	0.0252

Current control limits for 15 samples :
P Chart (Variable sample sizes):
p(ucl) = .101009
pbar = .319655E-01
p(lcl) = 0

Control limits of the first 10 samples :
p(ucl) = .108697
pbar = .319655E-01
p(lcl) = 0
<

Today's date : 17-Dec-88
Current time : 02:56 PM

Input parameters :
================
Initial seeds :
- seed1 = 2
- seed2 = 333
- seed3 = 56

number of sample in setup phase = 10
mean = 31
sd = 1
lower specification = 27
upper specification = 33
variable sample size :
- lower range = 40
- upper range = 60

no. of samples	sample size(n)	bad total	P=(x/n)	lower limit	upper limit	cumm. p
1	49	0	0.0000	0.0000	0.0000	0.0101
2	55	1	0.0182	0.0000	0.0475	0.0196
3	56	2	0.0357	0.0000	0.0712	0.0226
4	50	0	0.0000	0.0000	0.0624	0.0220
5	58	2	0.0345	0.0000	0.0696	0.0232
6	57	0	0.0000	0.0000	0.0626	0.0224
7	40	2	0.0500	0.0000	0.0858	0.0238
8	42	1	0.0238	0.0000	0.0855	0.0248
9	40	0	0.0000	0.0000	0.0811	0.0256
10	56	3	0.0536	0.0000	0.0798	0.0289
11	48	1	0.0208	0.0000	0.0843	0.0282
12	49	0	0.0000	0.0000	0.0793	0.0258
13	48	0	0.0000	0.0000	0.0761	0.0247
14	52	2	0.0385	0.0000	0.0774	0.0243
15	55	3	0.0545	0.0000	0.0813	0.0259

Current control limits for 15 samples :
Standardized P Chart :
p(ucl) = .812745E-01
pbar = .021576
p(lcl) = 0

Control limits of the first 10 samples :
p(ucl) = .830351E-01
pbar = .021576
p(lcl) = 0

Today's date : 17-Dec-88
Current time : 02:57 PM

Input parameters :
===============
Initial seeds :
- seed1 = 2
- seed2 = 333
- seed3 = 56

number of sample in setup phase = 10
mean = 8

no. of sample	no. of defects	no. of insp units	cbar/ ubar	lower limit	upper limit	cumm. defects
1	6	0	6.0000	0.0000	0.0000	6
2	4	0	5.0000	0.0000	0.0475	10
3	10	0	6.6667	0.0000	0.0712	20
4	11	0	7.7500	0.0000	0.0624	31
5	7	0	7.6000	0.0000	0.0696	38
6	11	0	8.1667	0.0000	0.0626	49
7	6	0	7.8571	0.0000	0.0858	55
8	15	0	8.7500	0.0000	0.0655	70
9	6	0	8.4444	0.0000	0.0811	76
10	7	0	8.3000	0.0000	0.0798	83
11	11	0	8.5455	0.0000	0.0843	94
12	7	0	8.4167	0.0000	0.0793	101
13	8	0	8.3846	0.0000	0.0761	109
14	3	0	8.0000	0.0000	0.0774	112
15	10	0	8.1333	0.0000	0.0813	122

Current control limits for 15 samples :
C Chart :
c(ucl) = 16.689
cbar = 8.13333
c(lcl) = 0

Control limits of the first 10 samples :
c(ucl) = 16.9429
cbar = 8.3
c(lcl) = 0

```
Today's date : 17-Dec-88
Current time : 02:57 PM


 Input parameters :
 ===============
 Initial seeds :
  - seed1 =  2
  - seed2 =  333
  - seed3 =  56

 number of sample in setup phase =  10
 mean                    =  8
```

no. of samples	refer-chart value	cusum	S+	S-	cumm. bad
1	6.0000	-2.3000	0.0000	-0.8595	6.0000
2	4.0000	-6.6000	0.0000	-3.7190	10.0000
3	10.0000	-4.9000	0.2595	-0.5785	20.0000
4	11.0000	-2.2000	1.5190	0.0000	31.0000
5	7.0000	-3.5000	0.0000	0.0000	38.0000
6	11.0000	-0.8000	1.2595	0.0000	49.0000
7	6.0000	-3.1000	0.0000	-0.8595	55.0000
8	15.0000	3.6000	5.2595	0.0000	70.0000
9	6.0000	1.3000	1.5190	-0.8595	76.0000
10	7.0000	0.0000	0.0000	-0.7190	83.0000
11	11.0000	2.4545	1.2595	0.0000	94.0000
12	7.0000	1.0379	0.0000	0.0000	101.0000
13	8.0000	0.6533	0.0000	0.0000	109.0000
14	3.0000	-4.3467	0.0000	-3.8595	112.0000
15	10.0000	-2.4801	0.2595	-0.7190	122.0000

```
Current control limits for  15  samples :
Cusum Chart for : (C Chart)
Upper decision limit    =  14.4049
Upper Reference value   =  9.74049
      Reference value   =  8.3
Lower Reference value   =  6.85951
Lower decision limit    = -14.4049
```

Today's date : 17-Dec-88
Current time : 02:58 PM

Input parameters :
===============
Initial seeds :
- seed1 = 2
- seed2 = 333
- seed3 = 56

number of sample in setup phase = 10
mean = 8
range of no. of inspection units :
- lower limit = 5
- upper limit = 10

no. of sample	no. of defects	no. of insp units	cbar/ ubar	lower limit	upper limit	cumm. defects
1	70	8	8.7500	5.6125	11.8875	70
2	39	5	8.2750	4.4156	12.1344	109
3	36	5	7.9167	4.1418	11.6916	145
4	71	9	7.9097	5.0973	10.7221	216
5	44	5	8.0878	4.2723	11.9033	260
6	41	5	8.1065	4.2866	11.9264	301
7	54	6	8.2341	4.7197	11.7486	355
8	54	8	8.0486	5.0395	11.0577	409
9	43	6	7.9506	4.4972	11.4040	452
10	57	9	7.7889	4.9980	10.5797	509
11	48	5	7.9535	4.1698	11.7372	557
12	69	9	7.9296	5.1137	10.7456	626
13	29	5	7.7658	4.0270	11.5046	655
14	46	5	7.8683	4.1049	11.6316	701
15	74	9	7.8919	5.0826	10.7011	775

Current control limits for 15 samples :
U Chart :
u(ucl) = 10.7011
ubar = 7.89185
u(lcl) = 5.08261

Control limits of the first 10 samples :
u(ucl) = 11.0479
ubar = 7.78889
u(lcl) = 4.52987

```
Today's date : 17-Dec-88
Current time : 02:59 PM

 Input parameters :
 ===============
 Initial seeds :
  - seed1 =  2
  - seed2 =  333
  - seed3 =  56

 number of sample in setup phase =  10
 mean                     =  8
 range of no. of inspection units :
 - lower limit            =  5
 - upper limit            =  10
```

no. of sample	no. of defects	no. of insp units	cbar/ ubar	lower limit	upper limit	cumm. defects
1	38	5	7.6000	3.9014	11.2986	38
2	71	8	8.2375	5.1933	11.2817	109
3	58	9	7.6398	4.8758	10.4038	167
4	88	9	8.1743	5.3152	11.0334	255
5	66	8	8.1894	5.1541	11.2248	321
6	66	8	8.1995	5.1624	11.2367	387
7	60	9	7.9806	5.1556	10.8055	447
8	43	7	7.7508	4.5940	10.9076	490
9	50	6	7.8156	4.3916	11.2395	540
10	55	6	7.9507	4.4973	11.4041	595
11	49	8	7.7847	4.8253	10.7441	644
12	63	8	7.7922	4.8314	10.7530	707
13	49	6	7.8210	4.3959	11.2462	756
14	76	8	7.9410	4.9520	10.9299	832
15	50	6	7.9671	4.5101	11.4241	882

```
Current control limits for  15  samples :
Standardized U Chart :
u(ucl) =  11.4241
ubar   =  7.96712
u(lcl) =  4.51014

Control limits of the first  10  samples :
u(ucl) =  11.0395
ubar   =  7.95067
u(lcl) =  4.86185
```

APPENDIX 9

RANDOM VARIATE GENERATION

In system simulation, random variates are used to represent the occurrences of the natural phenomena. Since in most cases, the decisions made on such a system are non-deterministic, the choice is normally based on probabilistic relationships (Graybeal and Pooch, 1980).

Random number generation

A random number generator plays an important role as a device that physically generate the random events in order to make the system simulation more realistic either physically (e.g. by throwing a dice) or mathematically. There are many mathematical methods of random number generation. One of the most widely used method is the congruent method as described by many authors (e.g. Martin, 1968; Shannon, 1975; Emshoff and Sisson, 1970; and Knuth, 1981). However, this method is device-dependent where the value of parameters depends on the 'word' size of the computer (see details in Knuth (1981)).

This study has used the method proposed by Wichmann and Hill (1987). The idea was to combine three generators to produce one random number which, according to their experiment, gave satisfactory results of an ideal generator : portable, efficient (e.g. fast speed) and written in high-level language. The program listing of random number generation named 'GEN_RANDOM' is shown in Appendix 7. Wichmann and Hill (1987) have tested their generator with three testing methods :- serial tests, poker tests and runs tests. Hence this study did not repeat those tests again but instead conducted the test of uniformity on five groups of starting seeds used in the exercise explained in Chapter 3. The results, shown in Table A9.1 to A9.5, concluded that the Wichmann and Hill (1987)'s generator can produce approximately uniform random numbers.

Table A9.1 Chi-square goodness of fit test for seeds group 1

seed1 = 1

seed2 = 10000

seed3 = 3000

range of data observed	observed frequency	expected frequency	χ^2
0.0 - 0.1	9978	10000	0.0484
>0.1 - 0.2	9888	10000	1.2544
>0.2 - 0.3	10087	10000	0.7569
>0.3 - 0.4	10239	10000	5.7121
>0.4 - 0.5	9946	10000	0.2916
>0.5 - 0.6	9895	10000	1.1025
>0.6 - 0.7	10065	10000	0.4225
>0.7 - 0.8	9999	10000	0.0001
>0.8 - 0.9	9836	10000	2.6896
>0.9 - 1.0	10067	10000	0.4489
sum of χ^2			12.727

$\chi^2_{.05,9} = 16.919$

Table A9.2 Chi-square goodness of fit test for seeds group 2

seed1 = 2

seed2 = 333

seed3 = 56

range of data observed	observed frequency	expected frequency	χ^2
0.0 - 0.1	9884	10000	1.3456
>0.1 - 0.2	10004	10000	0.0016
>0.2 - 0.3	9916	10000	0.7056
>0.3 - 0.4	9976	10000	0.0576
>0.4 - 0.5	10000	10000	0.0000
>0.5 - 0.6	10065	10000	0.4225
>0.6 - 0.7	10041	10000	0.1681
>0.7 - 0.8	10091	10000	0.8281
>0.8 - 0.9	10018	10000	0.0324
>0.9 - 1.0	10005	10000	0.0025
sum of χ^2			3.564

$\chi^2_{.05,9}$ = 16.919

Table A9.3 Chi-square goodness of fit test for seeds group 3

seed1 = 22217

seed2 = 2627

seed3 = 6307

range of data observed	observed frequency	expected frequency	χ^2
0.0 - 0.1	10032	10000	0.1024
>0.1 - 0.2	9895	10000	1.1025
>0.2 - 0.3	9864	10000	1.8496
>0.3 - 0.4	9939	10000	0.3721
>0.4 - 0.5	9857	10000	2.0449
>0.5 - 0.6	10048	10000	0.2304
>0.6 - 0.7	10101	10000	1.0201
>0.7 - 0.8	10003	10000	0.0009
>0.8 - 0.9	10103	10000	1.0609
>0.9 - 1.0	10158	10000	2.4964
sum of χ^2			10.2802

$\chi^2_{.05,9} = 16.919$

Table A9.4 Chi-square goodness of fit test for seeds group 4

seed1 = 4782

seed2 = 14062

seed3 = 9885

range of data observed	observed frequency	expected frequency	χ^2
0.0 - 0.1	10181	10000	3.2761
>0.1 - 0.2	10056	10000	0.3136
>0.2 - 0.3	10036	10000	0.1296
>0.3 - 0.4	9974	10000	0.0676
>0.4 - 0.5	9987	10000	0.0169
>0.5 - 0.6	10073	10000	0.5329
>0.6 - 0.7	9971	10000	0.0841
>0.7 - 0.8	9831	10000	2.8561
>0.8 - 0.9	9860	10000	1.9600
>0.9 - 1.0	10031	10000	0.0961
sum of χ^2			9.333

$\chi^2_{.05,9} = 16.919$

Table A9.5 Chi-square goodness of fit test for seeds group 5

seed1 = 777

seed2 = 12301

seed3 = 19

range of data observed	observed frequency	expected frequency	χ^2
0.0 - 0.1	9947	10000	0.2809
>0.1 - 0.2	10042	10000	0.1764
>0.2 - 0.3	9962	10000	0.1444
>0.3 - 0.4	9952	10000	0.2304
>0.4 - 0.5	10007	10000	0.0049
>0.5 - 0.6	10128	10000	1.6384
>0.6 - 0.7	10021	10000	0.0441
>0.7 - 0.8	10038	10000	0.1444
>0.8 - 0.9	9816	10000	3.3856
>0.9 - 1.0	10087	10000	0.7569
sum of χ^2			6.8064

$\chi^2_{.05,9}$ = 16.919

Normal random variate generation

Let x has normal distribution $N(\mu,\sigma^2)$

z has standard normal distribution N(0,1)

By inverse transformation :-

$$x = \mu + z\sigma \qquad .....(A9.1)$$

The idea is to generate z from uniform random numbers between 0 - 1 whose mean = 0.5 and variance = 1/12. From the central limit theorem applied to sums (Ott and Mendenhall, 1985), summing n standard uniform variates gives approximate normal distribution with

mean 0.5n and variance n/12 .....(A9.2)

The choice of n largely depends on the analyst, the larger value of n chosen, the better the approximation to the normal distribution (Graybeal and Pooch, 1980 and Hansen, 1985). Normally, n = 12 is recommeanded for it yields σ = 1 and a division operation is saved (Graybeal and Pooch, 1980). Thus equation (A9.2) becomes

mean 6 and variance 1 .....(A9.3)

Then transform (A9.3) to z of standard normal distribution

$$z = \sum_{i=1}^{12} U_i - 6 \qquad .....(A9.4)$$

from equation (A9.1), we have

$$x = \mu + (\sum_{i=1}^{12} U_i - 6)\sigma \qquad .....(A9.5)$$

Hence x is the normal random variate generated from equation (A9.5)

Poisson random variate generation

This approaches by counting the number of occurences in the Poisson process. Poisson variates are generated by counting the number of terms required until the cumulative probability exceeds a uniform variable on 0-1.

$$\text{Let} \quad P_i = \sum_{k=0}^{i-1} \frac{e^{-\lambda} \lambda^k}{k!} \qquad \text{.....(A9.6)}$$

where λ = mean of occurences

Let U = uniform random number

i = counter

N = generated number of occurrences

i will be counted until $U < P_i$

Then $N = i-1$ is the required number

Uniform random variate generation

This is for non-standard uniform (range $\neq$ 0-1).

$$\text{Let} \quad f(x) = \frac{1}{b-a} \qquad a \leq x \leq b$$

By inverse transformation :-

$$F(x) = \int_a^x \frac{dx}{b-a}$$

$$= \frac{x-a}{b-a}$$

where $F(x)$ = cumulative uniform distribution function

$$x = a + (b-a)F(x) \qquad \text{.....(A9.7)}$$

Let U = uniform random number

hence $U \equiv F(x)$

equation (A9.7) becomes

$$x = a + (b-a)U \qquad .....(A9.8)$$

Therefore x is uniform random variate of between range a and b generated from equation (A9.8).

To assure that the generators are valid in generating random variates, five groups of seeds were picked at random to test on the generator. With the sample of size 500, the means of generated variates were collected from three distributions : normal, poisson and uniform. The 98.8% confidence interval of of mean 30 and variance 1 as follows :-

$$29.862 < \bar{X} < 30.138 \qquad .....(A9.9)$$

The results shown in table A9.6, concluded that all sample means were lying within the 98.8% confidence interval which means that the three generators are valid for generating random variates with normally distributed sample means.

Table A9.6 The observed means of 5 runs from three different random variate generators

seed group	observed mean		
	normal	poisson	uniform
1 10000 3000	30.013	30.134	29.676
2 333 56	29.975	29.874	29.436
22217 2627 6307	30.076	30.436	29.932
4782 14062 9885	29.966	29.760	29.276
777 12301 19	30.045	30.036	29.534