A study of SPC Training Needs in Small and Medium UK Companies.

Claire Hewson
Richard Cox
and
Keith Stenning
Human Communication Research Centre
University of Edinburgh

June 2, 1997

Abstract

This report examines the implementation of Statistical Process Control (SPC) in a sample of six UK companies. Practices, problems, and training procedures are identified and compared in order to assess training needs. Recommendations are made for effective SPC training and a prototype training package is described.

Introduction

More and more UK companies, especially in the automotive industry, are using Statistical Process Control (SPC) due to ever increasing demands from customers. These pressures have emerged over the last ten or so years and have led to companies having to adopt new practices and procedures with which they were formerly unfamiliar. Introducing these new techniques is not a simple matter; effective implementation of SPC entails changes in employee responsibility and an increase in cognitive demands. The current study examines the nature of these changes, focusing on the interaction between social/organisational change and changes in knowledge/skill requirements. The objective is to identify how these changes make demands on training.

The study examines and compares in depth the SPC practices across a sample of six manufacturing companies. The companies in the sample display varying degrees of SPC implementation and report varying levels of success; differences between companies in factors such as employee responsibility and motivation at different levels, SPC methods and tools used, training materials and procedures used, etc. are observed. This report pinpoints these variations and identifies factors associated with the successful implementation of SPC, using these as a basis for making specific SPC training recommendations.

The foundational premise behind the application of SPC in manufacturing is that reduction of product variation by monitoring and controlling the process is more effective than an approach to quality based on 'final inspection'. SPC, if implemented successfully, should lead to reduced inspection and scrap costs.[1] However, there has been controversy concerning the degree of statistical and mathematical formality that is needed for effective SPC implementation.

Shewhart's SPC versus the 'mathematical approach'.

Shewhart's original conception of SPC in the 1920s emphasised that the variation in any process could be attributed to either 'common' or 'special' causes. Shewhart saw this distinction as fundamental in being able to control process variation. If a process is subject to variation only from common causes then it is considered to be in statistical control—it behaves in a predictable manner; however, if a process is subject to special causes then it is not predictable and is considered to be out of control. Shewhart's fundamental claim was that by eliminating special causes it is possible to keep a process in a controlled predictable state, and hence be able to minimise and predict product variation. The tool developed to identify common and special cause variation was the *control chart*; figures 1 and 2 below show control charts for in-control and out-of-control processes (see Wheeler and Chambers (1986) for details on the construction of control charts).

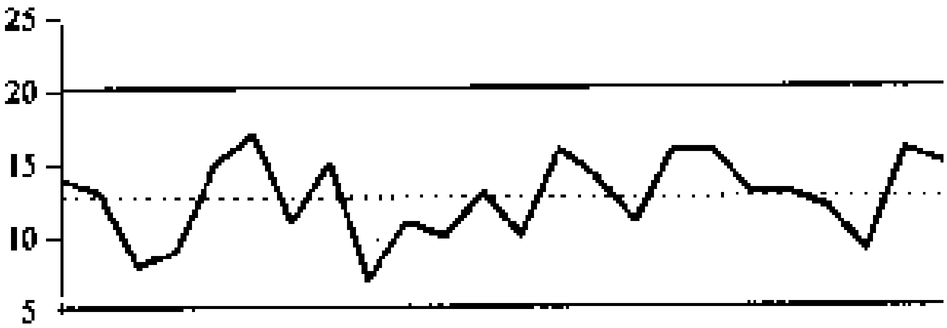


Figure 1: Control chart indicating in-control process

When the process is in control (only common causes of variation are present) points lie within the *control limits*, as in 1a; when one or more points lie outside the control limits, as in 1b, this indicates that the process is out of control (influenced by special cause variation). In the latter case action should be taken to identify and eliminate the special cause(s) of variation.

[1]Note that according to Starkey (1995) "...the greatest potential application [of SPC] is in non-manufacturing processes" (Starkey, 1995, p.116). While the application of SPC in a non-manufacturing context is acknowledged, it is maintained that SPC use in manufacturing is currently far more widespread and still suffers many problems; therefore the focus of this report is on the latter.

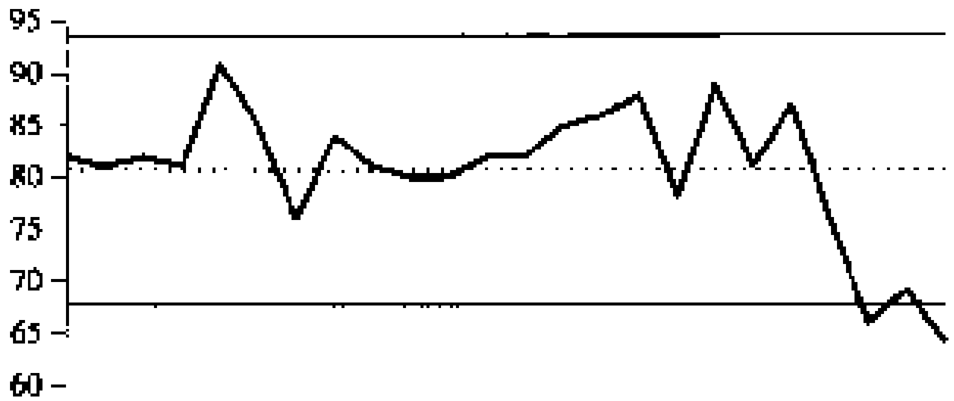


Figure 2: Control chart indicating out-of-control process

Essentially Shewhart's SPC was practical and presented a set of procedural guidelines for reducing process and product variation. Since Shewhart outlined his approach a number of statisticians have developed his ideas and attempted to provide a more sound theoretical mathematical foundation for his procedures. This move has resulted in the subsequent 'mathematical approach' which has become more widespread in the UK and Europe than Shewhart's original formulation (BDA, 1992). However, several authors (Starkey, 1995; BDA, 1992, eg) have attacked this latter approach and criticised it for "seriously reducing the potential of what may be accomplished through the use of SPC" (BDA, 1992, p.3). While this approach set out to fill in the gaps of Shewhart's SPC in terms of mathematical exactness, the BDA report (1992) makes the point that the assumptions made are restrictive in real world terms, and that this version of SPC is in fact weaker and less practical than Shewhart's original formulation. The essential contrast between these two approaches is summed up by Deming in a *verbatim* presentation in Versailles,

> What we need is an operational definition of when to look for a special cause, and when not to. That is, a rule which guides us when to search in order to try to identify and remove a specific cause, and when not to. It is not a matter of probability. It is nothing to do with how many errors we make on average in 500 trials or 1000 trials. No no no—it can't be done that way. We need an operational definition of when to act, and which way to act. Shewhart provided us with a communicable operational definition: the control chart using 3σ-limits. Shewhart contrived and published the rules in 1924—65 years ago. Nobody has done a better job since.

In contrast to Deming, Skillman (1996) has expressed a view more in line with the mathematical approach, arguing in an article examining SPC use in the fastener industry that

"Understanding the underlying mathematical postulates and statistical axioms is necessary to the successful SPC deployment" (Skillman, 1996, p.75). Skillman makes this comment while noting that many fastener companies lack personnel trained in statistical methods, and that often the "SPC Coordinators" appointed to design the SPC program and train the workforce have no background in mathematical statistics themselves. Skillman considers this statistical expertise to be important in order to be able to select the best fitting of the available mathematical models and choose the most appropriate SPC techniques for the processes at hand.

These two perspectives represent a dichotomy of opinion concerning the appropriate level of statistical sophistication for optimal SPC success. While the current study is less concerned with the theoretical underpinnings and statistical foundations of SPC and more concerned with the real world experiences of companies using SPC, the extent to which statistical expertise is required by the people who manage and implement SPC is clearly relevant to the current focus upon changes in organisational structure and cognitive demands associated with SPC. Thus, a key issue in identifying SPC training needs is what level of theoretical statistical knowledge is needed by employees at various stages in the SPC process. Here, the approach to answering this question is empirical. To this end, an instrument was developed in order to assess levels of SPC-relevant statistical/mathematical skill.

The remainder of the report presents the results of the study. Firstly the methodology and sample selection process is outlined, along with a brief account of the approach to data analysis adopted. Profiles of the companies are then given, focusing on general background details, organisational structure, and level of SPC useage. The SPC practices, procedures and problems are then compared across sites and salient themes identified. Finally the findings are interpreted and discussed, and recommendations made for effective SPC training practices.

Method

Selection Procedure.

The companies were approached individually and asked if they would take part in the study. They were selected from a list obtained from Sheffield Works Psychology Unit (SAPU), which contained a total of 35 companies, each with a rating (from 1 to 5) indicating the extent to which they used SPC. Companies which were rated as using SPC moderately to extensively were picked out and invited to take part in the study. Each company was sent a letter and a description of the project, and was then phoned a few days later. Of the companies approached, about 50% agreed to take part in the study. Seven companies were included in the final sample. However, the current report ignores data from the one company which used SPC in a non-manufacturing context since the present focus is upon SPC as applied to manufacturing processes.

Data Collection.

Each company was visited and a semi-structured interview was conducted, usually with the quality manager but in some instances with other people at managerial or supervisory level. The interviewee was selected on the basis that s/he had a comprehensive knowledge of the way SPC had been introduced and was currently being used within the company, as well as knowledge of the type of SPC training given. In some cases only one interview was conducted, but companies that were of particular interest and who were keen to continue to take part in the study were also given follow-up interviews. Each interview lasted between one and two hours and was audio taped.

The semi-structured interview schedule was designed to cover the following general areas, while allowing for exploration of other issues which might arise during the interview (protocol given in appendix A),

- Background details of the business; motivation for using SPC.
- Organisational levels in the company; responsibilities at each level; general education and experience at each level.
- Implementation of SPC: methods, tools.
- Training needs identified; skills/knowledge needed.
- Training given: materials, methods.
- Success of SPC/training; problems.

Data Analysis.

The audio recording of the interviews were transcribed, and the transcriptions used to carry out qualitative analysis of the data. The aim of this analysis was to provide as much detail as possible about the SPC practices, attitudes and experiences of each company, focusing upon identification of both similarities and differences between companies.

Initially each transcript was examined thoroughly so as to extract the information that was specified on the semi-structured interview schedule. This enabled direct comparison across companies for these particular questions/areas. Secondly, further analysis was carried out which involved scrutinising each transcript carefully in order to identify significant themes that arose during the interview, and which may not have been covered by the interview schedule (the approach used was similar to that described by Smith (1995). The themes and comments identified were compared across companies.

SPC Concepts Test

In addition to conducting interviews three of the companies were revisited and an 'SPC concepts' test administered to several of the operating personnel; the purpose of this test was to assess levels of formal statistical knowledge. In two of these companies four operators received this test and in the other company five operators received the test. These subjects were selected by the quality manager and/or production manager. The experimenter went through the test with each operator individually, reading out each question aloud and noting down the responses given. Subject and experimenter were both free to discuss the questions, and further explanation was given where necessary. Where possible the interaction was audio taped.

There were twenty three items on the test questionnaire covering a range of topics from basic arithmetic skills to interpretation of SPC charts and judgements about probability (see appendix B). The following section gives some background to the development of the SPC concepts test.

Development of SPC concepts test.

A literature survey of the statistics teaching literature was conducted in an attempt to find a suitable existing test. However, no suitable 'ready to use' instrument could be found so it was necessary to develop one. The literature search yielded a number of sources that provided ideas for developing test items[2]

An examination of the content of several statistics courses revealed that most introductory syllabuses assume that basic arithmetic operations are understood by students. By 'basic arithmetic' we include units, addition, subtraction, multiplication and division. For the purpose of this research, however (*i.e.* with a non-specialist trainee group such as SPC operators), it was felt to be important to detect basic arithmetic bugs and misconceptions.

In the the initial stages of test development, potentially useful concepts around which diagnostic items might be designed were extracted from the literature and listed. Three broad areas of basic statistical knowledge were identified - descriptive statistics, sampling and stochastics. For each of the three broad areas, sub-concepts were delineated and listed:

Descriptive statistics

This area typically covers collecting statistical material, arranging it and representing it appropriately. The notion of dispersion around a measure of central tendency (variance) is also included in the first area so, from the SPC perspective, these basic concepts are very important. Courses typically cover the following topics:

[2] The sources used in the SPC test development are referenced as the appendix entitled 'SPC test instrument development bibliography'.

- measurement, with stress on the notion that not everything has a natural yardstick
- effect of precision/resolution of measurement upon distribution shape
- use of tally sheets, tables, bar graphs
- how a frequency tally can show the distribution...often bell shaped, normally distributed
- individual characteristic values (highest, lowest, most frequent, least frequent)
- reading and constructing tables - idea of grid reference and conventions for referring (x,y), *e.g.* in context of table cell letter, number (e.g. 'B3'), use of squared (graph) paper, route directions
- stem and leaf plots – how they can reveal biases in recording *e.g.* body weight to nearest 0.5 kg
- use of stem and leaf diagram to find median
- use of the list - of items, a ranking list, tally list , list of classes, *etc.*
- summary statistics - central or typical value, range, spread
- meanings of term 'average'
- levels of measurement - nominal/categorical, ordinal/ranking, interval and ratio, formal and informal definitions ...
- measurement precision, representation precision
- continuous data - line graphs and frequency polygons
- diagrams of the matrix graphic variety — strip diagrams, pie chart, bar graphs, frequency polygon. When to use bar charts and when to use frequency polygons. Emphasis on appropriate assignment of graphs to tasks - *e.g.* graphs often useful for qualitative comparison of 2 or more values whereas tables best for precise read-off of particular values
- interpreting frequency distributions
- central tendency measures - calculating the median, mean
- characteristics and sensitivities of each measure of central tendency *e.g.* to outliers
- spread - interquartile range based on median
- box and whiskers plots

- sum of deviations - from median, from mean...implications
- standard deviation (SD)
- use of mean and SD... z-scores
- rules for symmetric 'normal' distributions 68% data=1SD, 96%=2SD, *etc.*

Misconceptions involving summary statistics Garfield & Ahlgren (1988) argue that, for many students, the 'mean' is a procedure - a computational act - rather than a concept. Many students tend to regard the 'average' as a usual or typical value (*e.g.* usefulness of city's average temp is judged to be 'it will tell you what to wear').

Sampling

This material covers qualitative and quantitative analysis of random samples:

- what does 'random sample' mean?
- why random sample (because population too large, or not accessible, selection destroys sample...) cars and borders examples (Abele, 1989)
- how the individual characteristic values (highest, lowest, most frequent, least frequent, mean value, median value) change when the individual values of the random sample changes
- comparing two random samples using the mean and standard deviation

Misconceptions in sampling There are a range of fallacies identified in the literature - *e.g.* base rate, large versus small samples and representativeness (Tversky & Kahnemann, 1974).

Stochastics

Comprehensive courses include:

- the history of probability - gambling, 17th century - Chevalier de Mare and Pascal and de Fermat...*etc.*
- basic definitions - random experiment; elementary outcomes; sample space
- random experiments - *e.g.* exercises such as plotting pattern of snowflakes on a roof (Green, 1989)
- the concept of trials

- gathering and presentation of data
- distributions of data
- coin-tossing experiments – 1 die, 2 dice, 3 dice...

  with the aim of encouraging ontological shift from listing outcomes to thinking about principles as complexity increases - *i.e.* to facilitate induction
- tree diagram representations of probabilities
- conventional nomenclature - probability formulae and notation
- asymmetrical probability - loaded die, spinners with unequal regions, and other examples
- understanding of independent, non-independent events
- understanding of with and without replacement
- sure events, impossible events
- mutually exclusive events, non-mutually exclusive events
- overcoming tendency to overestimate chance of 'representative' outcomes *e.g.* that series (8,14,23,31,42,47) is more probable than (1,2,3,4,5,6)
- logical operations (E AND F; E OR F; NOT E)
- conditional probability - addition rule for any events; addition rule for mutually exclusive events, subtraction rule, independence
- Bayes' theorem and false positives

Sources of difficulty for students in stochastics Garfield & Ahlgren (1988) provide a good overview of common student difficulties in the area of stochastics. They write that learning problems are often due to underlying difficulties with rational number concepts and proportional reasoning (fractions, decimals, percents, proportions, ratio etc). These should be screened for and remediated before any statistical training proceeds.

Another major source of difficulty lies in translating verbal problems into statistical notation. Yet another major source of misconceptions is the conflict of probabilities with students' experiences and how they view the world..

The work of Tversky and Kahnmann (*e.g.* 1974) shows that there students have misconceptions that go beyond *underlying* skills. They are intuitive convictions about statistical phenomena. An example is the ability to assess randomness.

Another key area is that of *representativeness* - especially in its *combinatorial* form. For example, people often judge the probability of a man being unemployed AND a trumpet player is commonly judged to be higher than the probability of a man being a trumpet player.

Tversky & Kahnmann also identify the notion of *availability* – easily brought to mind instances of a category. These are often judged to be more probable than less representative categories of event.

Without going into all reasoning fallacies, the conclusions in the literature seem to be that inappropriate reasoning is widespread and persistent, similar at all age levels, found even amongst experienced researchers, and quite difficult to change.

Implications for the design of training interventions

Several recommendations regarding teaching approaches emerged from the literature reviewed:

- introduction of concepts through concrete activities and simulations
- the use of visual illustrations and exploratory data methods
- advise to teach descriptive statistics alone without relating it to probability
- analysing common misuses of statistics in news stories, advertisements
- a need to recognise and confront common errors in students' probablistic reasoning

Schupp (1989) states that 'relative frequency' or 'probability' should not be introduced unless student understands proportion and of equality between proportions *i.e.* fractions, percentages, unitary ratio. Schupp (1989) also advises the use of computer simulations throughout whole of stochastics curriculum - animated, interactive simulations of sampling from urns of balls, spinners, playing cards, dice, *etc.*.

Taken together, these findings have numerous profound implications for SPC training. The recommended teaching approaches emphasise visualisation, interactive, animated simulations and the use of concrete materials. However, our research shows that these principles do not seem to be embodied to any great degree in current SPC training practice at any of the sites visited.

It was therefore decided that we should develop a prototype computer-based SPC training package[3] based on a dynamic simulation of a continuous process and using interactive graphical displays. Further details about SPC-ITE are provided below. The SPC-ITE prototype

[3] SPC-interactive training environment (ITE) developed collaboratively with Dr P. Cheng and colleagues at CREDIT, University of Nottingham.

was demonstrated to SPC personnel at one of the project sites (see below for report).

Item selection and item development for the SPC concepts test

As mentioned above, some of the items in the SPC Concepts test used here were derived from existing instruments - namely, those by Eltinge (1992), Pfannkuch & Brown (1996) and Pisani (1985). Other items, such as the basic arithmetic and calculation items, were developed 'from scratch'. Wherever possible, we attempted to pose test questions in a 'situated' way, using concrete examples from every day or factory life rather than abstract, more formal, mathematical conventions and notations. The final version of the instrument is appended in Appendix B.

Results

Company Profiles.

The following table displays the general summary data for each company. [4]

Company	*Product Area*	*No. Staff*	*SPC Yrs*	*Motivation*	*Procedures*
A (1)	Automotive	300	Apprx. 14	Choice	Manual
B (2)	Automotive	180	Apprx. 20	Customer	Manual
C (2)	Cutting Tools	200	7	Parent Company	Computerised
D (3)	Automotive	250	Apprx. 10	Customer	Manual
E (4)	Automotive	180	Apprx. 14	Customer	Computerised
F (4)	Cathode Tubes	?	Apprx. 6	?	?

Table 1: Overview of Companies Surveyed.

The number in brackets after each company's name indicates their SPC implementation/success rating.[5] The ratings assigned are based on the following scale which was constructed so as to best represent the range of status across the companies in the sample,

1. SPC working well—no perceived need or expressed plans to improve/extend.
2. SPC working okay but plans to improve/extend.
3. SPC running but seen as having many problems.
4. SPC not being used on the shop floor—perceived need to shift responsibility from quality team to production.

[4] In some instances certain details are not available, primarily due to the interviewee not having the specified information; these cases are marked in the tables by a question mark.

[5] Note that this rating is completely independent from the rating given on the original SAPU list.

As shown in the table, four of the seven companies in the sample were involved in making automotive components, one made cathode tubes, and one made cutting tools. All companies used SPC in a manufacturing context. The size of the companies ranged from 180 to 300 employees and the time elapsed since SPC was first introduced ranged from 6 to 20 years. In all but one case, where SPC was introduced purely by choice, motivation for SPC use was primarily customer oriented—to satisfy customer demands (though one company noted that pressure to introduce SPC came from the parent company). All the companies used discrete, as opposed to continuous, processes.

Organisational Levels.

Though the companies interviewed reported slightly different organisational levels, and used different labels for similar levels in the hierarchy, a common basic structure can be extracted which provides an approximate generalisation of levels across all companies. The purpose of this generalisation is to allow comparison of companies in terms of factors which may differ across the common organisational structure—factors such as level of education or extent of SPC related responsibilities at each level.

For all companies the levels reported can be broken down into the following basic organisational hierarchy,

- Director
- Manager
- Senior Supervisor
- Shop Floor Supervisor
- Operator

In each company there was a tiered system of management that comprised of several levels. In general the management hierarchy can be described as comprising of two basic levels, the lower management level—involving people such as the quality manager, operations manager—and the senior management, or director, level. Below the management level companies typically had a supervisory level, which also tended to fall into a two-tiered system. At the senior supervisory level supervisors were typically quality engineers, quality team members, and so on, who had responsibility for overlooking and maintaining the systems. The shop floor supervisory level consisted in operators/setters/team leaders whose job it was to supervise more directly production at shop floor level. Finally, the operator level consisted of people actually involved in production—machine operation—on the shop floor.

Level of Education.

The companies varied somewhat in general educational background and type of experience at each level. While details of specific qualifications at the various levels are sparse (due to the interviewee not having detailed information), it was noted by all companies that operating staff generally had very little in the way of prior knowledge of statistical and mathematical concepts, and tended to have had very little formal education. Companies consistently noted that SPC training for operators involved 'starting from scratch'. Regarding the other company levels, quality engineers and management tended to have experience and sometimes had done full-time college courses, while higher management were sometimes reported as being educated to degree level, and in one instance to doctoral level.

Implementation of SPC.

Procedures Used.

There was a fair degree of variation in the way SPC had been implemented in the companies. The two companies with an SPC status rating of 4 (E and F) had not yet started to use continuous process monitoring on the shop floor and were primarily using SPC to carry out process capability studies on pre-production runs. The other four companies using SPC in a manufacturing context were carrying out process control on the shop floor.

The company with the highest SPC status rating (A, an automotive component manufacturer) had used SPC across most processes but was now using it less as it was considered not very effective for tracking parts in a million, which customers were now demanding. However, SPC was being used in four areas of each of the engine valve spring department and the stabiliser bars department; it was noted that about 60% of operators would use SPC at some point in time. Quality assurance carried out capability studies; operators carried out manual measurement and plotting. A range of measurements were taken (length, diameter, attribute and so on) and all versions of control charts were used.

The company with the lowest SPC status rating (D) applied SPC across a range of processes. Plotting was done manually but mainly digital recording instruments were used. Operators used X bar R and attribute charts. Quality assurance carried out capability studies.

One of the companies with SPC status rating of 2 (B) reported using SPC on most processes. Quality assurance carried out CPK and PPK studies. Operators carried out manual measuring and plotting, using verniers and gauges, and mainly attribute charts but in some cases X bar R charts. The other company with the same rating (C) used SPC in most key areas. Operators in this company used micrometers to take measurements; these were linked up to feed straight into units which read the data and plotted a chart. The charts used were not standard X bar R, instead individual readings were plotted. Quality assurance supervised process/capability studies but operators collected the data for these.

To summarise the above data, two companies used SPC primarily for capability studies but not for process control; in these companies SPC was a function of the quality department and had not been pushed down to shop floor level. Three out of four of the remaining companies used manual plotting on the shop floor for process monitoring; these three companies all used both X bar R and attribute charts, and capability studies were carried out by quality assurance. The fourth company, however, had implemented computerised measuring and plotting methods; this company also differed in that capability studies were supervised by quality assurance but data was collected by operators, and X bar R charts were not used—individual readings were plotted.

In terms of linking SPC success with particular methods used there is no obvious relationship beyond the basic need to push SPC down to shop floor level and undertake continuous process monitoring. The data does not indicate that either manual or computerised measurement and plotting methods are superior, or that any particular versions of charts or measuring tools are associated with greater success.

Responsibilities at Levels.

Cheng and Dawson (1996) outline a set of categories for describing the range of SPC related duties at each level of organisational structure in the companies they surveyed. The current data, however, do not provide enough detail from each company for analysis to this level of specification. Nevertheless, the general picture of where SPC responsibilities lie across the basic levels of organisational structure is available for each company, as outlined below.

The two companies who had not pushed SPC down to the shop floor did not involve operators in the SPC process; one of these companies, F, did feed back the information about the SPC data collected to operators but this information was reported as not being used or acted upon. In both of these companies SPC was a function of the senior supervisor/management level (quality assurance) whose role it was to carry out capability studies and ensure robust systems. In company E the SPC technician was primarily responsible for these duties and for gathering and analysing all SPC data in general, under the supervision of the operations manager. In company F the quality manager supervised these procedures, working with the quality assurance team. In each company the data gathered was assessed and reviewed by senior supervisors and management.

In the remaining four companies operators were involved in running SPC to varying degrees. Operators were required to measure, plot, and interpret charts. All companies also required operators to act to keep the process in control but to call a supervisor if the actions required were beyond their capabilities. The expectancies on operators to actually be able to rectify problems appeared to vary between companies. Company C noted that operators were expected to steer the process themselves but could bring in the maintenance people if there was something they couldn't rectify. Company A described operators as acting as the 'warning lamp', noting that they make adjustments to keep a process in control if it is within their capabilities but if it is something like fixing a part of a machine their job is to identify the fault and get an engineer in who is qualified to fix it. Company D noted that operators were generally not making process adjustments themselves, but were having to call in quality engineers or setters. Company B stated that operators were not expected to take any action until they had managed to locate the problem; they were then required to fix things if possible or otherwise call a supervisor. In the company which used computerised measuring and chart plotting methods, operators were also required to carry out capability studies and set up machines themselves, whereas in all other companies this was the role of quality assurance or supervisory level.

SPC responsibilities for the above four companies at director level tended to be minimal, involving at most the reviewing of SPC data in meetings. Company A stood out as different in this respect in that there was a lot of responsibility for introducing and organising the whole SPC system from the managing director. The quality manager and engineers in this company oversaw the running of SPC on a more day to day basis and conducted capability studies and engaged in shop floor supervision. In the other companies the role of overseeing and organising SPC was more specifically the responsibility of the management and senior supervisor levels, with little input from director level. In these companies the quality team was expected to ensure that the systems were in place and carry out/supervise capability studies and ensure in control processes. They were also responsible for gathering SPC data to review in meetings.

From the above brief outline several features stand out. First, the company with the highest SPC rating was unique in the level of involvement in SPC from director level. This supports the claim (Starkey, 1995) that support from higher management is important for successful SPC implementation. Second, the companies with the lowest SPC ratings failed to pass any SPC duties to operators; this finding isn't surprising given that a prime goal of SPC is to push responsibility for quality down to operator level through methods of process control—thus companies that fail to do so will not be considered successful. Third, there is some indication that the ability of operators to identify and rectify problems is associated with success since the least successful company using shop floor SPC reported problems in that operators were generally not making process adjustments. The more successful companies reported higher levels of operators making such adjustments.

Cheng and Dawson (1996) introduce the notion of a 'tight' SPC process cycle, which relates to how tightly the activities in the SPC process cycle are distributed across the employee levels. They conclude "It appears that small cycles which involve less people and on fewer levels of the organisation are correlated with more successful use of SPC in the companies studied." (Cheng and Dawson, 1996, p.23). The current data presents a more complex picture than this, indicating that involvement in SPC from a range of levels is important for successful implementation. Most important is pushing responsibility for SPC down to operator level such that operators are responsible for collecting and recording data, and to as great an extent as possible interpreting and acting upon this data. Secondly support from higher management is important. The data suggests that support and involvement in SPC across all levels is important, within the appropriate designated roles.

SPC Training.

Training at Different levels.

Table 2 shows for each company the type of training given at each level of organisational structure.

Company	*Director*	*Management*	*Senior supervisor*	*Shop floor supervisor*	*Operator*
A (1)	Self-taught/ books	Self-taught/ books	Self-taught books/experience	Class/ hands on	Class/ hands on
B (2)	Interactive video	Interactive video	Ext. course video	Interactive video/ class /hands-on	Interactive video/ class /hands-on
C (2)	Interactive video	Interactive video	Interactive video	Interactive video /hands-on	Interactive video /hands-on
D (3)	?	Ext. course/	Ext. course/	Ext. course/ class /hands on	Classroom/ hands on
E (4)	None	External course	External course	None	None
F (4)	None	OU course	None	None	None

Table 2: General training at different levels in the company.

First note that neither of the companies with the lowest SPC rating had embarked on any SPC training within the company, though one or two people at senior supervisory and management level had been on external training courses. These were the two companies which are noted above as not having achieved a shift of responsibility for quality and process control down to shop floor level. Nevertheless, both these companies expressed a need to achieve greater process control on the shop floor and giving SPC training to operators was seen as an important prerequisite for achieving this.

The other four companies did report more extensive training programs. The company with the highest SPC rating was unique in that both director and management levels were self-taught, making use of books on SPC and total quality management. This company noted that when they started to look at SPC there were very few training materials and courses around, and any materials that were available were pitched way beyond shop floor level. Thus they needed to develop their own training materials for shop floor staff which were initially put together by the managing director and an in-house psychologist. One of the quality engineers who had gained experience of SPC methods while working in Japan was involved in teaching other people at managerial and senior supervisory level. The operator and shop floor supervisor levels were given internal classroom and hands on training. At a later stage an outside consultant was brought in to deliver training at the operator level.

The company with the lowest SPC rating did not mention any specific SPC training at the director level. Management, senior supervisor, and shop floor supervisor levels had all been on external SPC courses (in some cases training of trainer courses). A consultant was brought in to train people in the company. Senior supervisors received some training from the quality manager. Operators and shop floor supervisors received both classroom and hands on training from various other company levels and from the outside consultant.

Company B (rating 2) used interactive video training[6] at all levels in the company, including management and director levels. The SPC facilitator, senior supervisor level, tended to go on external courses and bring information back to train operators; the quality manager also trained operators. Operators and shop floor supervisors received classroom training and hands on training as well as the interactive video.

The other company with SPC rating 2, C, made major use of SPC interactive video training. It was stated that all levels in the company went through the interactive video training. In addition, operators and shop floor supervisors were given hands on training by senior supervisors. There was no mention of other training given at the management and senior supervisor levels.

While it is worth noting that both the companies reporting moderate SPC success made extensive use of an interactive video SPC training package, used across various levels within the organisation, the company who reported most SPC success did not use interactive video techniques at all. Neither did the company undertaking operator training who reported least success with SPC. Thus, while interactive video appears be effective, to some extent, for presenting SPC training materials, it is clear that alternative methods are also effective. Probably the most noteworthy feature which distinguishes the company with the highest SPC success rating from all the other companies is that both management and director levels were self-taught, and self-motivated. The least successful company, however, reported no specific

[6] This training comprised of a set of discs developed by Lasermedia for one of this companies main customers; the same interactive package was used by company C.

SPC training at the director level, though fairly extensive training was given at other levels.

Training of Operators

In all four companies which delivered SPC training to operators both hands-on and theoretical presentation methods were used. 'Hands-on methods' refers to actual training on the shop floor, using SPC in the manufacturing processes to which it will ultimately be applied. Theoretical training refers to any other training methods that were used, including interactive video training, classroom talks, classroom practical excercises, SPC related excercises, and so on. The tables below examine the type of training materials and strategies used by each of the companies who undertook training of operators (including the shop floor supervisory level). Tables 3 and 4 examine the nature of the theoretical materials used and the range of and extent to which abstract theoretical (statistical) concepts are presented. Tables 5 and 6 look at the training practices and strategies used for theoretical and hands-on training methods respectively.

Company	*Interactive video*	*Booklets*	*Presentation/ talks*	*Practical examples*	*Directly related to job*	*Excercises/ problem solving*
A (1)	No	?	Yes	Yes	Yes	Yes
B (2)	Yes	?	Yes	Yes	No	Yes
C (2)	Yes	No	No	Yes	No	Yes
D (3)	No	Yes	Yes	Yes	No	Yes
E (4)	-	-	-	-	-	-
F (4)	-	-	-	-	-	-

Table 3: Theoretical training materials presented to operators (relating to training within the last 3 yrs).

Materials. One feature that stands out from the above table is that the company with the highest SPC rating is unique in relating its theoretical training materials directly to the operators' job. While the other companies did incorporate practical examples into their training materials, these examples did not focus specifically on the actual processes that were used on the shop floor (though they may have been similar in that they used the same dimensions of measurement etc.). In contrast the company with the high SPC success rating did indicate that their materials were continually updated and tailored so as to directly address the application of SPC to the specific processes used on the shop floor.

Company C stood out in that it did not use any classroom presentation of theoretical materials but this factor appears to be unrelated to SPC success. There was also a difference between companies in whether interactive video training was used, but again there was no indication that this factor was related to SPC success ratings.

Company	*histogram graphs*	*Average*	*Distribution*	*Variation*	*Standard deviation*	*Probability*	*Formulas*
A (1)	Yes	?	No	?	No	No	No
B (2)	Yes	Yes	Yes	Yes	Yes	No	?
C (2)	Yes	Yes	?	Yes	?	?	?
D (3)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
E (4)	-	-	-	-	-	-	-
F (4)	-	-	-	-	-	-	-

Table 4: Statistical Concepts Taught

Concepts Presented. Interestingly, Table 4 shows that the company with the highest SPC rating did not attempt to present theoretical statistical concepts to operators, beyond explaining the basic technique of representing data by histograms/graphs. In contrast the least successful company which presented training to operators did attempt to present relatively advanced statistical notions, such as standard deviation, as well as presenting relevant formulae.

It is worth noting that the successful company pointed out that while abstract presentation of these concepts was not considered appropriate for operators, because of their lack of formal mathematical education, it was considered that the more practically oriented training given did lead to an implicit understanding of these notions, as they related to the job at hand. The moderately successful companies did tend also to go through more abstract presentation of statistical concepts than did the most successful company. These companies both stated that a basic grasp of the notion of variation was essential for operators able to effectively implement SPC. The issue of the extent to which operators need to grasp abstract statistical concepts in order to understand and effectively use SPC is explored further in the next section.

Training Practices. Several factors relating to training practices and strategies with respect to presentation of theoretical material stand out as noteworthy. From the information given in Table 5 it is possible to identify several factors that appear potentially to lead to more successful implementation of SPC. Three of the practices—namely, mastery learning (i.e. going over material until grasped), identifying individual needs, and using one-to-one training—are seen to be used by all but one of the four companies. Further, the one company which does not use these training practices has an overall less successful SPC rating (rating 3) than the other three companies (ratings 2, 2, and 1), thus suggesting that these three factors may be instrumental in producing successful implementation of SPC.

Table 6 confirms the potential role of these factors with respect also to hands-on training.

Company	*Mastery learning*	*Assess performance*	*Identify indiv. needs*	*Group discussion*	*One-to -one*
A (1)	Yes	Yes	Yes	?	Yes
B (2)	Yes	Yes	Yes	Yes	Yes
C (2)	Yes	Yes	Yes	No	Yes
D (3)	No	Yes	No	No	No
E (4)	-	-	-	-	-
F (4)	-	-	-	-	-

Table 5: Practices relating to theoretical training of operators (relating to training within the last 3 yrs).

Company	*Go over until grasped*	*Assess performance*	*Id. ind. needs*	*Group sessions*	*One-to -one*
A(1)	Yes	Yes	Yes	?	Yes
B(2)	Yes	Yes	Yes	Yes	Yes
C(2)	Yes	Yes	Yes	No	Yes
D(3)	No	No	Yes	?	Yes
E(4)	-	-	-	-	-
F(4)	-	-	-	-	-

Table 6: Practices relating to hands-on training of operators (relating to training within the last 3 yrs).

Again the less successful company is alone in failing to adopt the practice of mastery learning, suggesting that this practice is important for training effectiveness. In addition, this company is the only one who does not report assessing performance as part of hands-on training.

However, in the case of hands-on training the least successful company did identify individual needs and give one-to-one instruction, which it did not do for theoretical training. But even for hands-on training this was only done to a limited extent; it was reported that on observing that some of the operators did not know how to use a calculator they were subsequently given some basic maths instruction and taken through how to use a calculator on a one-to-one basis. This was only done with some operators, however, and to a minimal extent.

Statistical expertise and SPC use.

As noted earlier the issue of whether an abstract grasp of the underlying statistical principles associated with SPC is necessary in order to successfully implement it is a potentially controversial one. The companies surveyed presented a range of opinions on this issue. The managing director of the company with the highest SPC rating clearly took the line that presenting such abstract concepts was unnecessary and innapropriate: "...you can give them enough, if you like, verbal interpretation of the statistics for them to have a rationale for it. But we never attempted to actually go through the statistics." In this company it was noted that that operators could come to 'have a feeling' for what SPC is about without going directly through the statistics. Other companies appeared to assume that a certain level of presentation of abstract concepts, especially the notion of variation, was an important part of SPC training.

The degree to which presentation of abstract mathematical and statistical concepts is necessary for using and understanding SPC is especially relevant in light of the typically low level of formal education of operating staff. Getting operators to grasp some of these abstract concepts is likely to require extensive training. The data presented in the previous section suggested that an understanding of abstract concepts (e.g. standard deviation, normal distribution, etc.) may not be necessary in order to understand the basic principles of SPC, at least to the level of being able to successfully implement it. Having said this, however, there are certain notions that seem intuitively central to attaining a proper understanding of SPC techniques—perhaps the concept which appears to be most central is that of 'variation'. It is difficult to see how the methods of SPC can be appreciated without having an understanding of variation. Starkey (1995) considers this notion to be of prime importance for appreciating and understanding the role of SPC: "An understanding of variation is essential in order to interpret data" (Starkey, 1995, p.129)

With the aim of exploring this issue further, as well as examining the general level of numeracy and basic mathematical skills amongst target trainees, the SPC concepts test was administered to operators in three of the companies. The Tables below presents subjects' responses to the items on the questionnaire, along with information about their mathematical and SPC experience.

Basic maths skills of operators.

Firstly, the table shows that most of the subjects did not have any formal qualifications in mathematics. Secondly, all but one subject in the sample had undergone some form of SPC training; however, four of the subjects (D-s3 and D-s5, A-s1 and A-s3) had only had a very minimal amount of training. Given that the majority of subjects in this sample had already been given some SPC training this data does not readily provide a measure of the skills of target trainees prior to training. Clearly it is possible, if not likely, that the training given might have influenced and changed subjects' prior-to-training mathematical knowledge and skills.

Nevertheless, the one subject who had received no SPC training and the four who had

Subject No	*Maths* Quals	*SPC* Training	*SPC* Use	*Answer* Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
D-s1	None	Yes	Yes	All	4.2	45	c	d	60	b	36.5	Ot	c
D-s2	None	Yes	Yes	a,b,c	4.2	45	a	d	62	b	37.5	c	c
D-s3	None	Yes(?)	No	a,b,c	4.2	61	c	b,c,d	55	a	80	c	c
D-s4	None	Yes	Yes	X	4.2	70	c	d	55	b	45	c	c
D-s5	None	Yes	Yes	a,b,c	4.2	X	c	d	60	b	50,60	b,c	c
B-s1	None	Yes(?)	No	a,b,c	4.2	45	c	d	60	b	36.5	c	c
B-s2	None	Yes*	Yes	a,b,c	4.2	35/9	b	d	60	b	36.5	b	c,a
B-s3	None	Yes	Yes	a,b,c	4.2	45	c	d	60	b	36	b	c
B-s4	None	No	No	All	4.2	45	c	X	60	a	X	b	c
A-s1	None	Yes(?)	Yes	All	4.4	45	b	d	58	b	36.5	c	c
A-s2	CSE	Yes	Yes	All	420	45	c	d	60	Same	36.5	c	c
A-s3	CSE	Yes(?)	Yes	All	4.2	45	c	d	60	b	36.5	c	b
A-s4	No	Yes	Yes	a,b,c	4	45	c	d	65	b	X	c	c,d

Table 7: Subjects' responses to items 1 to 10 on SPC concepts test.

received very little training [7] can reasonably be treated as displaying prior-to-training mathematical skills. A comparison between these subjects and those who did receive more comprehensive training could give some insight into the effects of SPC training on basic mathematical knowledge/skills.

An initial glance at the data reveals some interesting observations. Some of the questionnaire items were more consistently responded to across subjects than others. Three of the twenty three items received the same answer from all subjects: Q15, Q16 and Q23. Nine of the remaining eighteen items received the same answer from all but one, two, or three subjects (i.e. over 79% of subjects): Q2, Q4, Q5, Q7, Q10, Q11, Q13, Q19 and Q22. Responses to the remaining ten items showed less agreement between subjects.

In order to look more specifically at what these different items relate to, each question was categorised below in terms of the knowledge/skills that it is testing (Table 8).

The three items in the Table 8 which are marked with an asterisk are those which relate directly to SPC procedures.

If we look first at the three items showing high inter-subject response agreement (in each case subjects gave the correct answer) these deal with reading graphs and tables, and plotting points. These are skills which are basic and fundamental to being able to use SPC. Even the subjects who had not had any SPC training answered these questions correctly, including one item which related directly to SPC practices. Table 2 shows that the questionnaire also

[7] One of these subjects was classified by the quality manager as someone who had not had any training, since the training undergone by this subject was so little compared with the other subjects interviewed from this company. The other subjects stated themselves that they had only had a very small amount of training.

Subject	*Answer*												
No	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23
D-s1	c	c	c	Girl	Thurs	Tues	18	8	74	X	b	c	
D-s2	a	c	b	Boy	Thurs	Tues	17	8	74	X	b	b	
D-s3	c	b,c	a	Either	Thurs	Tues	17	19	70,80	X	b	c	
D-s4	c	a	c	Boy	Thurs	Tues	Mon	X	74	X	c	c	
D-s5	c	a	c	Either	Thurs	Tues	15-19	8	74	✓	b	c	
B-s1	c	c	c	Either	Thurs	Tues	15	X	74	Opp	d	c	✓
B-s2	c	d	c	Boy	Thurs	Tues	17	8	74	X	Ot	c	✓
B-s3	c	c	c	Boy	Thurs	Tues	17	8	74	Opp	d	c	✓
B-s4	c	a	c	Either	Thurs	Tues	17	8	74	✓	c	c	✓
A-s1	b	a	c	Girl	Thurs	Tues	17	15	74	Ot	b	c	✓
A-s2	c	d	c	Either	Thurs	Tues	17	8	74	✓	c	c	✓
A-s3	b	c	a	Boy	Thurs	Tues	17	8	74	✓	b	c	✓
A-s4	c	a	a	Either	Thurs	Tues	19	8	74	✓	b	c	✓

Table 8: Subjects' reponses to items 11 to 23 on SPC concepts test.

contained three further questions dealing with reading graphs/tables (Q6, Q10 and Q19) and one other dealing with plotting points (Q20) which were not answered correctly by all subjects. However, two of the former questions (Q19 and Q10) were answered correctly by all subjects except one, each of whom was 'untrained' and one of whom didn't use SPC at all, the other item (Q6) had five incorrect responses which can be reasonably treated as 'minor innacuracies' rather 'errors' (refer to appendix A). The other question which concerned plotting points and was primarily answered incorrectly involved plotting (x,y) coordinates and it was clear that most subjects had not come across this method before. This contrasted with the plotting question which was answered correctly which gave the x and y axes concrete variables (time and temperature).

The above data suggest that operators who have undergone SPC training do possess, to a reasonable extent, the basic skills of reading measurements and reading and plotting graphs, especially when these relate to concrete rather than abstract variables. The items on the questionnaire which elicited more correct answers from subjects all related to these basic skills. While the ability of the 'untrained' operators to answer these questions correctly may suggest that these skills are already in place prior to training, it must also be noted that these subjects did state that they had seen other people using control charts etc. and hence may have learnt through observation. Further investigation would be needed to clarify whether these skills are a result of SPC training.

The questions for which *most* subjects gave the same answer (omiting Q19 and Q10 which have already been discussed above) dealt with reading measurement scales, probability,

Competency/Skills	*Question*
Simple calculations	Q1, Q3
Reading measurement scales	Q2
Probability	Q4, Q11, Q12, Q14, Q21, Q22
Normal distribution	Q5
Reading graphs/tables	Q6, Q10*, Q15, Q16, Q19
Variation	Q7
Averages	Q8, Q17
Random sampling	Q9*
Plotting points	Q20, Q23*
Rations	Q 13
Range	Q18

Table 9: Categorisation of questionnaire items according to skills/knowledge tested

normal distribution, variation, and ratios. There was only one questionnaire item on both distribution and on variation and the majority of subjects gave the correct answer to these questions. The same two 'untrained' subjects answered each of these questions incorrectly, and the variation question was also answered incorrectly by a third subject who had received SPC training. This finding indicates that SPC training may lead to understanding of normal distribution and, more tentatively, variation which was absent prior to training.

There was also only one item relating to ratios, and whilst most subjects agreed upon an answer to this question the preferred answer was in fact incorrect.

There were six questions dealing with probability, of which three received general agreement in responses and three did not. Two of the probability questions asked about the likelihood of a single event occuring (Q21, Q12), while four asked about the likelihood of an event occuring *given* a specified sequence of prior events (e.g. after tossing a coin eight times and getting heads what do you expect to get on the ninth toss of the coin)(Q4, Q11, Q14, Q22). The data shows that in general subjects performed much better on the latter type of probability question. Two of these questions were answered correctly (i.e. subjects agreed that the chance of a single independent event occuring was not altered by the recent history of events) by all subjects except one, and the incorrect answer came from the same subject each time; another of these questions was answered correctly by all but three subjects. It was surprising, given this pattern, that the fourth question (Q14) in this category elicited a variety of responses with no clear preferred answer. The other two probability questions, which asked about the relative chances various single events occuring, also displayed a variety of responses with no clear prefered answer.

The above data indicate that subjects perform better on probability questions which ask about the likelihood of sequences of independent events (since three of the four such questions on the questionnaire were answered correctly) than on probability questions asking about the relative likelihoods of single events (both such questions elicited a range of answers, some correct and some incorrect). There is no evidence that trained subjects perform better than 'untrained' subjects on these questions.

The remaining items on the questionnaire, which elicited some correct responses but also a range of incorrect responses, tended to deal with carrying out basic mathematical calculations, e.g. calculating average and range. Subjects did not perform as well on these questions and there was no observed effect of training on subjects' responses.

To summarise the above discussion of the data in relation to the question of the level of basic mathematical knowledge and skills of operators, it was found that both trained and untrained operators tended to perform well on questions relating to, reading graphs and tables, and plotting points. However, in qualification to this observation it was found that performance diminished when graphs were not given concrete axes variables, and that there was sometimes inaccuracy in reading graphs. The lack of an observed difference between trained and untrained operators suggests these skills may be in place prior to training; however given the small sample size and other confounding factors (operators may have picked up these skills by watching others use SPC) no firm conclusion can be drawn.

The questions on normal distribution and variation were also answered correctly by most subjects; interestingly the subjects who answered these questions incorrectly were both untrained (though one trained subject also answered the variation question incorrectly) providing tentative evidence that SPC training improves understanding of these concepts. This evidence suggests that subjects do not have a good grasp of these concepts prior to training.

The probability questions which dealt with the likelihood of a single independent event following a sequence of events were generally answered correctly; in contrast the probability questions dealing with relative likelihoods of separate single events were not generally answered correctly. There appeared to be no difference in performance of trained and untrained subjects on these questions, suggesting that SPC training (in particular the training experienced by these subjects) does not affect people's reasoning about probabilities.

Lastly, the questions which subjects performed most poorly on tended to be those which involved carrying out basic mathematical calculations. Again, whether or not subjects had received SPC training did not seem to affect performance on these questions.

Relationship between Maths Skills and SPC Skills

The above discussion looked at the data in terms of the performance of machine operaters on questions testing basic mathematical skills. Areas of proficiency were noted as well as areas of weakness and differences between operators who had already received SPC training and those who had not. A closer look at the responses given to the questionnaire items gives a richer insight into the relationship between SPC skills and basic mathematical skills.

One noteworthy feature of subjects' responses to several of the items on the questionnaire was the tendency to relate these questions directly to the SPC procedures they used.[8]

In many cases this method was useful—for example subjects' all (except one) manged to answer question 10 correctly by relating the run charts presented to those they had seen or used on the shop floor and in SPC training. In many cases it was apparent that subjects were interpreting abstract concepts in a very specific and procedural way which may not necessarily represent a general abstract understanding of the concept. Nevertheless, this method was often successful in providing the correct answer suggesting that subjects did have some grasp of the underlying concept in question. One subject approached question 7 about variation by thinking of variation in a specific procedural way. When asked "How do you think about variation, I mean how would you go about...?" this subject replied "You'd times it by five. You take five variations and then you divide by five". This subject also commented "Well that goes two up and then it goes down. There's no sums there..." "This has got more variation because the figures between them are wider..." These comments suggest that while thinking of variation in terms of the specific procedures he uses, this subject also has a more abstract understanding of the concept of variation. This subject answered this question correctly.

Note that the question on variation was one of those for which it was suggested (in the above discussion) that training may have had an effect of subjects' responses, since it was primarily untrained subjects who failed to answer this question correctly. The other question for which this was the case was the normal distribution question (Q5). Again subjects related this question to specific procedures which they were familiar with and answered the question correctly. One subject commented, pointing at the correct answer, "yeh, but that gives you a better average" and commented that he had used the same kind of method at union courses to work out wages. Several subjects, however, noted that their answer was based on commonsense, or their knowledge of men's heights.

Another question which subjects tended to interpret in terms of the specific proceudres they used was question 9 which asked about how best to take randomly sampled products from a production line. Most subjects who were using SPC chose to answer that they would take x samples per y mins. When asked to transfer that method into one of the answer options given in the question subjects all rejected (a) and were about equally divided between (b) and (c).

Thus, there was some application of specific knowledge of SPC procedures and techniques to some of the items on the questionnaire—in particular those questions which were obviously dealing with SPC, production methods, control charts, and so on. This knowledge when applied typically helped in producing the correct answer, especially in relation to the questions

[8]Subjects were told that they were to be given an 'SPC test' so were expecting to be required to apply their knowledge of SPC in answering the questions.

on variation and normal distrbution.

Many questions, though, were not seen by subjects as relevant to SPC and their answers were based on commonsense 'guesses'. These questions were the probability questions, but also involved questions relating to basic mathematical calculations which were not directly related to SPC practices. One such example of the latter was the question which asked subjects to work out the average speed for a particular journey; another was that which asked about the way in which the ratio of two mens ages would change with the passage of time. Subjects did not perform very well on these items. Performance on the probability questions was better. However, there were some clear instances of a basic misunderstanding of some aspects of probability by some subjects; for example two subjects made comments which indicated that they interpreted the statement 'The likelihood of a baby being a boy is about 1/2' (Q9) as meaning that there is *more* chance of a baby being a boy.

To summarise the above observations, subjects applied SPC knowledge mainly to questions that were clearly directly relevant to SPC and sometimes to more abstract questions. This application of knowledge did tend to help in chosing the correct answer in both cases. Subjects did not explicitly apply SPC knowledge to questions relating to basic mathematical calculations and did not perform very well on these questions. Neither did subjects apply their SPC knowledge to probability questions, though they appreared to perform reasonably well on several of these questions. These observations do not allow any definite conclusions about the relationship between basic mathematical skills and sucess at SPC. However, they suggest that operators, at least, do not see their SPC knowledge as being related to abstract or domain-unrelated mathematical calculations or to abstract or domain-unrelated notions of probability.

In order to investigate further the relationship between SPC knowledge and knowledge in these other areas we can compare performance on SPC questions and non-SPC questions for each subject, and also relate this to level of SPC expertise. From the data given in table one no relationship was observed between performance on questions directly related to SPC and performance on other questions—in particular, it was noted that subjects were not consistent in their answers to these questions. That is, subjects did not consistently answer either the basic maths or probability questions either correctly or incorrectly; instead the correctness of their answers was eratic. However, the three questions directly related to SPC were generally answered correctly. This finding suggests that the SPC training given equips SPC users with knowledge which is specific to the procedures and processes they carry out, and which does not generalise to more abstract knowledge of the concepts involved and their application in other domains. While this looks in general to be the case there was evidence that the concepts of variation and normal distribution may be attained, during SPC training, in a more abstract manner.

The important question, though, is whether SPC users need a grasp of such abstract mathematical principles and ideas in order to successfully use SPC. The current data indicates that the users in the current sample do not show a correlation between their SPC and basic maths skills. In fact, the sample displayed quite poor performance on basic mathematical skill items which were not to do with plotting and reading charts and tables. An observed relationship between success at SPC and level of basic maths ability could shed some light on this issue. If people were found to be using SPC successfully while still displaying poor basic maths skills then this would suggest that a domain specific procedural knowledge of SPC was adequate for its effective use.

As noted, the basic maths skills of the SPC users interviewed were generally poor, and there was little variation between subjects in terms of overall general ability at these items. The subjects came from three individual companies from the sample in the current survey. One of these was the company rated as least successful with SPC, one was rated as moderately successful, and the last was rated as most successful. However, from the data gathered there was no clear difference observed in the extent to which subjects from each of these companies performed correctly. Though it is interesting to note that the measurement question was answered correctly by all subjects in the two less successful companies but incorrectly by three out of four subjects from the most successful company.

One subject interviewed (B-2, marked with an asterisk in the table) was exceptional in that he was official SPC coordinator/facilitator and had undergone advanced SPC training, and acted as SPC trainer for the company. This subject was still found to answer several of the probability and basic maths questions incorrectly, suggesting that SPC training does not influence these skills even at advanced level. When asked what he thought of the test he replied "it's terrible", pointing out that the questions posed had very little to do with knowledge of SPC.

To summarise, the data discussed here have displayed several interesting findings for the sample observed; the extent to which this data should be generalised is unclear given the limited number of subjects and the selection procedure available. The findings are firstly that SPC users typically report having no formal qualifications in mathematics (two out of thirteen had CSE maths).

Secondly it was found that most subjects tended to be competent at the questions relating to reading graphs/tables and plotting points, regardless of whether they had received SPC training or not. The questions on variation and normal distribution were answered correctly by most subjects; further the incorrect answers to these questions came primarily from subjects who had not had SPC training, suggesting that the SPC training may affect knowledge about these concepts. Subjects gave varied responses to the questions about probability, both correct and incorrect, showing both between and within subject inconsistency across this category of questions. However, it was noted that performance tended to be better on those probability items which dealt with the likelihood of an event occurring *given* a specified sequence of prior events, rather than those which asked about the relative chances single events occuring. Finally, subjects did not perform very well on items which related to carrying out simple mathematical calculations.

Further examination of the answers subjects gave indicated that they did explicitly apply their knowledge of SPC procedures wherever it was clear that the questions were directly relevant, but rarely when the questions were not directly related. No evidence was found to suggest a relationship between level of SPC competence and level of basic mathematical competence in other domains not directly related to SPC. In fact the data suggests that the knowledge of the SPC users interviewed seems to be domain specific rather than abstract and generalisable.

Problems and Comments about SPC.

Several interesting themes emerged from the data. This section looks at these themes, identifying commonalities and differences across companies.

SPC Implementation.

Several companies noted a tension between customer demands and company needs in terms of the SPC practices used. Company A (rating 1) had been involved in disputes with one of their main customers over which SPC methods and procedures were most useful; the customer wanted SPC to be run according to the guidelines they set out whereas the company felt that their own methods were more appropriate. This company managed to convince the customer that their methods were effective and continued to use these. Company E (rating 4) also commented that the SPC demands imposed by customers were often not especially useful or beneficial; however, these methods were adhered to even though the quality manager stated that there was often not enough emphasis on continuous shop floor monitoring (customers were happy to sign off a pre-production proof of capability), and that SPC should be used on more processes. It is interesting that the company who took more control in selecting SPC procedures appropriate to their needs displayed more success.

Company C (rating 2) also noted that they did not stick rigidly to standard SPC techniques (i.e. X bar R charts) but chose procedures which they felt were most appropriate for their needs. They were using non standard process control methods; for example, operators were plotting individual product measurements directly onto charts rather than taking the average of a sample of products. This company reported a reasonable level of success.

Flexibility in being able to adapt standard SPC procedures for use with specific processes may be instrumental in aiding the successful implementation of SPC. Several companies did express doubts about the extent to which SPC was applicable and useful for some of their processes. Company A noted that SPC was not much use for tracking parts in a million, which was now becoming a customer requirement; for this reason SPC was being used less than before. Company D noted that some of their processes involved gradual machine wear and thus were not appropriate for applying SPC; additionally, it was reported that operators had put in complaints to the quality department that they were affecting their production by imposing SPC methods. Company E noted that because they had to keep very tight tolerances they needed very expensive dedicated gauging equipment for taking measurements; this was one factor influencing why process control had not yet been pushed down to shop floor level. Some of these problems, such as the latter, may be difficult to overcome, but others may be tackled by being innovative in the development of appropriate process control methods.

There was a difference between companies concerning the extent to which SPC use was customer oriented. Company A started out using SPC for its own benefits and under their own motivation; all the other companies were initially responding to customer pressure in adopting SPC procedures, but company C (rating 2) reported that SPC was now also used because it was seen as a useful tool. The quality manager for company E stated that he wanted to use SPC for its own benefits. Companies B (rating 2) and D (rating 4), however, seemed primarily still motivated by the customer.

One major common view across companies, whether or not they had managed to achieve this, was that production should be responsible for controlling the parts. It was consistently noted that the role of the quality department was to maintain the systems and get processes in control in the first place, but that it was the operators role to keep these processes in control and have the prime responsibility for quality of the product. Companies F (rating 4) and E (rating 4) hadn't yet achieved this but expressed it as a prime goal,

> To be fair, the only people that are doing SPC is the quality department...I really don't want to get too embroiled in it. I would much rather—production are making the parts, production should control the parts. That's the mentality; and let QA look after the systems, and look after the initiatives for moving us forward (Quality Manager, Company E).

Company E attributed this failure to push responsibility for controlling the parts down to production level to the prevalence of an old attitude to quality throughout most levels in the company, especially higher management level; also noted was that the SPC technician, who was also the setter, was often too busy setting up machines to run SPC effectively.

Companies A (rating 1), B (rating 2), and C (rating 2) reported having achieved—to some extent at least—this shift of responsibility for quality down to shop floor level. A major factor in this shift was that operators were responsible for process monitoring and for *acting* to solve problems. Company D (rating 3) was less successful than the latter three companies in that operators were in many cases failing to act to solve problems and keep processes in control. It was noted by both companies B and D that the operators are the people that really know what is going on with the processes, and understand the nitty gritty of how things work.

> ...because we rely on the operators talents. They're the people doing the job, and they're they're the people that are going to see all the variations and all the nitty bits that go on. We could go along today, now, and stand there for five minutes, and we see a fraction of what really goes on (Quality Manager, Company B).

Thus getting operators to act to solve problems was seen as particularly important, and is likely a major factor in achieving SPC success.

A further common theme was that SPC was treated not in isolation but as a part of the whole total quality system. A variety of other quality methods and tools were used and SPC was just one of these.

The use of manual methods, at least for training purposes and often as part of ongoing SPC procedures, was recommended by most companies. Company A (rating 1) had deliberately kept things manual so as to keep things 'personal' and give ownership to the operators. It was commented by the managing director that using computerised methods would depersonalise things and operators would be less likely to take any notice of the charts produced.

> They're just done on paper—and there's a logic behind that aswell; the logic is it's their chart. Once it becomes in the machine it's all depersonalised. Yeh, it does depersonalise it. They're less likely to actually take any notice...(Managing Director, company A).

This opinion was also confirmed by the Quality Manager of company A, who noted that in the last place he looked at which had a computerised system, the process was out of control but nobody was taking any action,

> So the guy used to put the spring in, push the button and the measuring device, whatever he'd got to measure, and plotted it. And it was inching along and no-one was taking any notice of it. 'Cause everybody thinks—looks at it—uses it as a television set basically (Quality Manager, company A).

Companies B (rating 2) and C (rating 2) noted that manual methods were highly beneficial for training purposes, though both these companies also expressed the benefits of moving on to using computerised measuring and plotting equipment so as to speed things up. Companies E and F confirmed this view, even though they had not yet embarked upon specific SPC training, maintaining (respectively) that manual training methods would make people react a lot quicker and would provide a good simple presentation format.

Several comments concerning 'overcontrol' were noted. Company E pointed out that many companies when first starting to using SPC fall into the trap of trying to control processes to unnecessarily tight limits; this is not only uneconomical timewise but also can lead to unmanageable numbers of charts everywhere. Companies C and B confirmed this view that it was not always necessary to continually monitor processes which were already proven to be well under control. Company C made the further point that operators sometimes became very extreme and fussy, wanting every part to be exactly the same as the next; in this case it was necessary to re-direct them. This was identified as a training requirement that tended to be omitted, i.e. training people not to overcontrol.

Effectiveness of SPC.

A range of factors relating to the effectiveness of SPC implementation were raised by companies. A major theme concerned motivation at different organisational levels. Most companies made a point of stating that an understanding of and involvement in SPC across all levels in the company was essential for successful SPC implementation. Companies B, C, E and F emphasised this point, noting that an awareness of SPC at all levels in the company was very important.

> ...there's no point in asking an operator to do SPC and react to that in control conditions if you haven't got the backing to put it right. So it's a pointless exercise. So, yes, managers and—well right from the top downwards—need to know what the concepts are and what we're trying to achieve (Quality Manager, company B).

Company E (rating 4) identified lack of motivation as a major problem, both at managerial and operator level. Company D (rating 3) also reported problems with motivation at managerial and operator level; higher management were reported as not taking an active enough role or interest in SPC. Setters were indentified as a particular hindrance to successful SPC: operators were perceived to be detecting out of control conditions effectively, but the problem was seen as lying with the setters, whose role it was to make machine adjustments, and who were failing to take action when operators did report out-of-control conditions. This was considered a motivational problem. In turn, operators then became demotivated because no-one was taking any notice of their warnings. Company B (rating 2) reported the same problem, setters were not taking any action when approached by operators who had noted out-of-control conditions. In both companies this was noted as leading to operators 'fixing' the charts so that the process looked in control. However, whereas company B had largely overcome this problem, through training, it was still a major issue for company D. Company A (rating 1) reported no current problems with operator motivation, though this was identified as a problem initially,

> ...if they think they're there as a spy they'll fiddle them (Managing Director, company A).

The problem was overcome by emphasising that the charts were not acting as a spy, and by giving operators responsibility to act and keep their process in control; this was seen as giving them pride in their work and inducing motivation to perform well. Note that this company stood out in that there was a high degree of motivation at higher management level.

As well as motivation being identified as a factor instrumental in leading to the problem of operators fixing readings, it was also noted that this problem could be accountable to lack of understanding or skill. Companies C and D both made this suggestion.

> We honestly believe they're not doing it deliberately, not doing it to deliberately mislead, they're doing it because they think that it's alright to do it. But they're deliberately putting wrong readings down. Because we think—-they're not seeing them as control lines, we think they're seeing them as specification lines. So they see a reading that would be out of the control lines and they put a different reading down, so that all the measurements are within the control lines, because if it goes out they've got to stop the machine and rectify it (Quality Manager, company D).

Company F suggested operators were using gauges incorrectly (in the few instances where operators were taking measurements), leading to erroneous readings; it was believed that using digital measuring tools would improve the accuracy of these measurements. These problems were generally attributed to a lack of skill and understanding due to inadequate training. Company D (rating 3) identified a lack of understanding across all company levels of the basic motivation behind SPC as a major problem. However, it was also noted that there had been a lot of investment in SPC training, indicating that the problem was not lack of SPC training but ineffective training. Company C (rating 2) reported that SPC when first introduced failed completely because there was no understanding of why it was there, due to a lack of training. Only later, when training was given more focus, did SPC start to work. In general companies tended to identify this type of understanding at a very general conceptual level, i.e. understanding why SPC is there and what it is trying to achieve, as a major need. This finding supports that of Cheng and Dawson (1996).

Companies B, D and F all noted the problem that some people who were being asked to use SPC had been given no training at all.

> People are using callipers out there and we haven't specifically trained them to use callipers. I think they're just given callipers and said, well, you use these callipers (Quality Manager, company F).

Company E pointed out that the SPC technician made errors—in particular, he was reported to be averaging averages which the quality manager considered to be an incorrect procedure. This was attributed to inadequate training.

In general, companies tended to attribute many of their problems to a combination of lack of motivation and lack of understanding. These problems were in turn associated with a lack of adequate training. There were, however, other factors (related to motivational and knowledge issues) which were identified as contributing to the level of SPC success. One common theme was the importance of seeing the benefits of SPC in order to acquire an appreciation its function. Company D noted that the processes where SPC was successful could be identified as those in which operators were able to see directly the benefits of SPC, in contrast to the less successful processes for which this was not the case.

> In the MRP section they saw—not immediate, but a very quick improvment—within the department, as I explained, through changing tolerances and things. At the other coiling section, they don't see an improvement in the department; the improvement comes in the next department and if they don't go and work in the next department and know what the problems are they don't see the improvement. I think that's a big part of the problem to be honest. They don't see an improvement, therefore they don't see the reasons for doing it properly (Quality Manager, company D).

Companies B and C also noted this factor as important in producing SPC success. Compant F, although not using shop floor SPC yet, noted that feeding back SPC information to the operators was important in giving them motivation and encouragement to improve their performance.

Company D further noted that the processes for which SPC was more successful involved SPC monitoring and action/adjustments being carried out by the same people. This was in contrast to the less successful applications where the operators carrying out process monitoring had to call in setters to take actions. Other companies noted the importance of getting the people involved in process monitoring to also be involved in taking action, as far as possible. This is related to the emphasis on giving operators prime responsibility for maintaining process control. In addition company D noted that operators did not need to stop a machine in order to make adjustments for the processes where SPC was more successful.

Several benefits of SPC were noted, including assessing process capabilities (companies A, C, D and F); reduction in inspection costs (companies A and C); operators taking more care over their work (company A); operators stopping unnecessary fiddling with the machines and instead using SPC data as a basis for making more effective adjustments (companies A and D); adapting and improving machines (company C).

Training Practices.

A range of training practices were noted as instrumental in leading to SPC success. Company A (rating 1) was the only company who related their theoretical training directly to the processes used on the shop floor. Other companies reported using analogous examples, for instance examples in which the same dimension was measured (company B), but did not directly relate theoretical training to the specific processes operators worked with. Direct tailoring of materials, then, may be helpful.

Another important factor in training seemed to be 'mastery learning'; that is, going over and over training with people until it was clear they had grasped the concepts/procedures presented. The more successful companies reported adopting this practice; company A identified mastery learning as particularly crucial in training operators. Company C also noted adopting this practice. Company D (rating 3), however, identified failure to follow up on training sufficiently as a problem. Related to this factor is the feature noted by several companies that getting SPC up and running takes a long time, in particular because of the amount of training that is needed. Company A (rating 1) noted that it took about two years to get SPC working effectively across the whole workforce; company C (rating 2) highlighted the way in which the introduction of SPC involves a very gradual change in 'culture'.

> I think it's a cultural thing. It's nothing you can suddenly switch all the people to a different gear...Changing the culture from 'I will just operate my machine and someone else will sort it out' to the people actually now starting to look after their processes, and know the tools, and know why they are doing it—that sort of crucial change (Quality Manager, company C).

Companies A and C both emphasised the need to educate the whole company, pointing out that SPC success is not something that can happen quickly. Company F also stated that while the very basics of SPC can be grasped quickly, to understand SPC fully takes a while. Both the companies which recognised and accepted the time investment that was needed displayed relative success.

Assessment was also seen as a very important part of SPC training. Company A (rating 1) commented that increasing the number of assessment exercises in their training program proved to be more successful. Companies C (rating 2) and B (rating 2) also highlighted the importance of assessment. Company B, however, did identify the lack of assessment of long term knowledge as a drawback in their own training; exercises were presented shortly after training and were viewed as limited in that they only tested short term knowledge. This was related to the need to provide refresher courses, which was perceived as not currently done to the extent that it should be. Company A were the only company that did explicitly mention organising continual refresher courses for operating staff. However, companies B and C both clearly did provide some follow up training where it was needed; both noted identifying and addressing individual needs, and company C in particular described a training needs plan which kept an up-to-date record of the skills operators had and the skills they needed for the job they were doing. Company D (rating 3) did provide assessment as part of training but while noting that operators were not performing well on the exercises, did not mention any attempts to go back over the training materials with them.

Another feature noted as important for operator training was to present material in very small chunks. Company A stated that they limited their training sessions to half an hour. Company C pointed out that operators could not be expected to sit and take in material for more than an hour or so at a time, stating that operators were given time to sit and absorb the presented information before moving onto the next video training disc. Allowing operators to take an active role in training was also seen as important. Most companies noted the importance of providing practical hands-on training. Company C saw the interactive video package as being particularly good because it actively involved trainees; company B, on the other hand, said that operators tended to get bored with this video package and placed more emphasis on involving them through simple practical exercises and group discussion.

There were a couple of other points of disagreement between companies concerning the best training practices. One concerned whether group or individual trianing was most effective; company C noted that operators were less intimidated and performed better when left alone with the interactive video training, whereas company B found that going through the video package in groups was preferable since it provoked more discussion and got people thinking together as a team. Another controversy was the extent to which abstract statistical concepts should be presented to operators, who typically had very little formal training in mathematics and statistics. Company A (rating 1) clearly stated that presentation to operating personnel of the statistics behind SPC was not necessary or useful, and this was not attempted.

> You can give them enough, if you like, verbal interpretation of the statistics for them to have a rationale for it. But we never attempted to actually go through the statistics (Managing Director, company A).

Company B (rating 2) noted that people really only need to know 'the basics' and made a point of keeping the presentation of any statistical theory very simple and grounded in practical demonstration as far as possible. Company D (rating 3), while not having a clear line on this issue, did stand out in that the materials they used did go into the statistical concepts underlying SPC, even going through formulas for calculating CPK values etc.

Company A (rating 1) made a point of stressing that operators should move straight into applying SPC as part of their job after training, as opposed to training and then leaving a gap; they took care to ensure this practice. Company D (rating 3) did not adopt this practice, identifying failure to follow up the theoretical training materials on the shop floor as a problem. This difference may in part account for the different levels of SPC success experienced by these two companies.

Other problems included the observation from company E that many people in the company had actually been on training courses, but were unable to apply this knowledge because they were not being asked to be involved in SPC; the only person that really carried out SPC procedures in this company was the SPC technician. A further point more commonly raised by companies was that there was an unmet need to assess peoples' prior levels of SPC related knowledge before giving training. Companies B and D commented that knowledge was assumed which it was later found operators did not possess (for example how to use a calculator). Company E also commented that assessing knowledge prior to training would be useful.

Finally, concerning the factors guiding the development and adoption of training practices, company E pointed out that there was pressure to use the training packages that had been developed by the customers who were demanding the adoption of SPC practices.

Discussion

Company Profiles.

There is no indication from the current data that any of the company profile factors—product area, company size, number of years since SPC was introduced, and use of computerised or manual procedures—are associated with level of SPC success.

It was observed, however, that the most successful company was unique in that motivation for introducing SPC came from higher management, as opposed to customer pressure. This can most effectively be explained as an indication of a higher degree of commitment and motivation from director level in the most successful company, resulting in greater SPC success. Such motivation and self-direction is best explained as effective by directing more resources towards SPC training. A reluctance from director level to invest a lot of time and effort into SPC training and implementation would clearly be a hindrance to successful SPC implementation.

Level of Education.

Level of education of operators was identified by Cheng and Dawson (1996) as related to SPC success; in their sample it was noted that the companies with the highest SPC rating were the ones with the best qualified and trained operators. This finding was not confirmed in the current sample; however, all the companies in this sample reported that operators generally had a very low level of formal education and none mentioned any formal qualifications held by operators. This was confirmed by the sample of operators who received the SPC and basic mathematics skills test—two out of thirteen operators in this sample reported having a CSE maths qualification; both these operators were from company A (rating 1). In general, there was not enough information about levels of education across the companies in this sample to draw conclusions about the relationship between educational levels and SPC success.

SPC Procedures.

A major factor identified as linked to SPC success is whether or not SPC is pushed down to shop floor level. The two least successful companies were the only ones who had not yet started to implement continuous process monitoring on the shop floor, instead limiting SPC to capability studies carried out by quality control. Beyond this basic need to push SPC down to shop floor level there was no evidence that any of the particular SPC procedures reported—whether computerised or manual, or any of the various types of recording and plotting methods used—were more successful than others.

However, it did appear to be the case that the less successful companies were more customer led in terms of the procedures and techniques they adopted. These companies reported conforming to customers' demands concerning the SPC methods they used, while also noting that these methods were not as effective as they could be. The more successful companies, however, also tended to report a tension between the methods they felt were most appropriate for their processes and the demands imposed by customers, but noted that they negotiated with customers in order to be able to stick to the methods they preferred. Thus, there is some indication that adaptability and self-directedness in choosing appropriate SPC methods is linked with SPC success.

A further interesting observation, reported by company D, was that whether or not operators had to stop a machine to make an adjustment was a factor which distinguished successful from non-successful applications of SPC. For the processes where SPC was working effectively operators did not need to stop the process in order to take process adjustment actions.

SPC Responsibilities at Organisational Levels.

Cheng and Dawson (1996) present the notion of a tight SPC cycle, claiming that there is a correlation between tight SPC cycles and level of SPC success. That is, cycles which involve fewer people and on fewer levels are correlated with SPC success.

The current data supports a somewhat different interpretation. First, it was noted that SPC awareness and responsibility at all levels in the organisation was important. In particular, a lack of involvement from higher management and operator levels was seen to be particularly detrimental. The two least successful companies had failed to involve operators in SPC at all and noted this as a major hindrance; one of these companies, E, also noted the lack of backing from higher management as a problem. Company D (rating 3) also reported a lack of support from higher management as problematic. Company A (rating 1), on the other hand, had not only strong backing at higher management level (as noted above) but also reported high SPC involvement at operator level. Companies B (rating 2) and C (rating 2) had both pushed a fair amount of responsibility down to operators and reported reasonable levels of involvement from higher management. Thus the data indicate that backing for SPC across all company levels is important for success.

However, more specifically, certain duties and responsibilities can be identified as most effectively implemented at particular levels. All companies noted the goal of getting responsibility for controlling processes with the operators, while responsibility for maintaining the systems was viewed as with quality assurance, and responsibility for reviewing and directing resources with higher management. The level to which this structure had been achieved, however, varied across companies; the more successful companies were closer to this ideal than were the least successful companies. In all four companies who had implemented shop floor SPC, operators were taking measurements and plotting these on charts; however, in the least successful company operators were typically failing to take actions based on this information. The more successful companies did report operators interpreting and acting on the basis of the information they gathered, thus suggesting that operator action is probably an important factor for SPC success.

In relation to the notion of tight SPC cycles, the current finding is that diffusion of as much responsibility as possible for process control to operators is a desired and effective outcome, but also that responsibility for helping to maintain SPC systems is an important need at other levels, especially higher management. The less successful companies reported less support from higher management, suggesting a positive correlation between higher management motivation/support and SPC success. [9] The most important point seemed to be to ensure that the responsibilities at each level were being carried out effectively: note that companies B and D both reported that setters/shop floor supervisors were causing problems by failing to respond to operators reports of out-of-control conditions. One way to overcome this may be to devolve the supervisory responsibilities down to operator level—however, this may be difficult and involve a lot of further training in the necessary machine setting skills. Alternatively, ensuring adequate SPC training and understanding at the supervisory level

[9] It must be pointed out, however, that the interview with the successful company which reported strong management backing was conducted with the managing director, whereas all the other interviews were conducted with the quality manager. Thus it is possible that the differing reports could be an effect of differing perspectives. However, it was felt that this was unlikely.

may be a better solution to overcoming this problem.

In sum, the idea of tight SPC cycles leading to SPC success is not wholly supported by the current data; rather it is suggested that as much responsibility for process control as is possible should be pushed down to shop floor level. However, also of fundamental importance is to maintain a degree of SPC responsibility across all company levels, and to ensure that each level is effective in carrying out their SPC-related role. The way to achieve this is through effective training.

Training Practices.

The first point that stands out in relation to SPC training is that adequate training at director level appears to be important; the most successful company was the only one where higher management were extensively trained (through self-teaching methods). In other companies higher management received little training and were generally minimally involved in SPC. Thus adequate training at director/managerial level was identified as a major need.

The second major need was effective training at operator level. Most companies recognised that training operators to use SPC was time consuming. The managing director of the most successful company noted that it took a long time to get SPC working effectively across the workforce: "first time we did it....to get it working reasonably efficiently across about three hundred people took us, probably about two years." It was also noted, however, that there was a lot of trial and error involved in this process of getting SPC up and running. Had this company had access to well-motivated guidelines as well as an outline of effective training strategies (of the type which the current project aims to generate) then the time taken to get SPC running efficiently would certainly have been considerably reduced. Instead the company were working blind, in that they had to develop and test their own training materials and methods because of the lack of courses and materials available—especially for training at operator level—at the time they started using SPC.

The current data suggests strategies and practices which prove to be most effective in training operators. The key to effective and successful training of operators seems to be not only related to the amount of training given, but to the way training is delivered. The following factors relating to training materials and practices are identified as of prime importance in contributing to successful implementation of SPC.

- Assessing performance before and during training and using this assessment as a basis for identifying individual needs.

- Giving training on a one-to-one basis such that individual needs are catered for, with emphasis upon repetition of areas which prove problematic for the individual (mastery learning).

- Presenting materials so that they are directly related to the relevant manufacturing processes.

The above items are identified as the most salient factors for successful training, based on the data gathered. The most successful company in the survey used all of the above techniques, while the least successful company used few of them. The companies which showed moderate success were seen to use the first two techniques above, but did not use the third—tailoring theoretical materials to relate directly to the manufacturing processes used. Thus we have three factors which the survey data strongly suggests combine to produce effective training.

Further factors relating to successful training materials and procedures can be extracted from the data. Regarding the type of concepts presented, an emphasis on simple presentation, grounded as far as possible in practical demonstration, was found to be more prevailent within the more successful companies. Company A (rating 1) was the most extreme in terms of avoiding abstract presentation of statistical concepts, noting that beyond presentation of a histogram operators were not given theory about the statistical concepts underlying SPC; rather, training was very much based on procedural applied knowledge. In contrast, while incorporating some hands-on training, company D (rating 3) used materials which did present fairly abstract statistical principles (though practical examples were also given). Company B (rating 2) and company C (rating 2) both presented some statistical notions, but placed a lot of emphasis on practical demonstrations of these notions. This pattern suggests that a grasp of abstract statistical theory is not necessary for operators to successfully use SPC, and that procedural knowledge is adequate.

The data from the SPC/maths skills test also supports the above conclusion. In general operators were found to have quite poor abstract mathematical/statistical skills and tended to approach the questions presented in such a way as to suggest that their understanding of concepts such as variation, distribution, and so on were grounded in procedural knowledge. There was no apparent difference in the skills of operators from companies with differing levels of SPC success. Subjects, in general, performed better on the items relating to plotting and reading graphs, especially when these were concrete rather than abstract, and worse on items which involved more abstract mathematical calculations. However, there was some indication that SPC training did lead to a more abstract grasp of the notion of variation, since most subjects were able to identify which of two sets of numbers showed more variation; incorrect answers to this question came primarily from untrained subjects.

Subjects' approach to the probability questions was based on commonsense and anecdotal knowledge, and they displayed no consistent theory. Most subjects opted for the conclusion that you cannot predict the outcome of random events.

The current data suggests not only that presentation of abstract principles is not necessary for SPC success, but that it may even be a hindrance. In the context of the generally very low level of formal education and mathematical experience of the operators in the companies seen, it is plausible to suppose that presentation of abstract concepts and formulas could serve to demotivate operators, while avoiding this kind of depth and abstraction may allow them to approach the training with more interest and confidence. This tentative conclusion, however, deserves further investigation and clarification. Variation, for example, is a notion that would appear to be central in understanding SPC (see Starkey (1995)), and the evidence presented here suggests that trained subjects have acquired a more abstract sense of this notion. On the other hand, there was evidence that subjects did not have such a clear abstract understanding of the notion of probability, which is interesting in the context of the BDA report's (BDA, 1992) statement rejecting the idea that this latter notion has an important role to play in understanding SPC. Clearly a more comprehensive study would be needed to expand on these initial observations.

Related to the emphasis upon simple practical presentation of training materials is the emphasis upon using manual methods for training. Most companies explicitly mentioned the importance of using manual measurement and plotting methods in order to train operators, and several noted that they had deliberately stuck to manual procedures because it was felt these would lead to greater SPC success. One company, though, conceded the need for manual training but noted that computerised methods had then successfully been applied.

A further factor identified as important in training operators was that they should be able to see the benefits of SPC. This was noted by several companies, and usually applied to the hands-on training since theoretical training materials generally tended not to allow such direct observation of benefits. Company D identified this feature—being able to directly observe the beneficial effects of SPC—as distinguishing between the processes where SPC was successful and those where it was not.

The more successful companies also noted that training had to be delivered to operators in small chunks. Thus training sessions were typically limited to somewhere between half an hour and an hour. This was noted as preventing trainees from losing their attention span and getting tired, as well as giving them time to digest smaller chunks of information at a time.

A factor which distinguished Company A (rating 1) from company D (rating 3) was that in the former company operators were taken straight from SPC training to applying SPC in their job. Company D did not adopt this practice, and noted the failure to follow up theoretical training materials on the shop floor as a problem.

Recommendations

To summarise, the following training practices have been identified as conducive to successful SPC implementation,

- Training across all levels of the company
- Providing a general conceptual understanding of the role and benefits of SPC
- Assessing level of SPC related knowledge prior to training
- Keeping presentation simple, practical and directly related to the job
- Avoiding in depth presentation of abstract theoretical principles underlying SPC
- Showing directly the benefits of SPC
- Providing an active role in training with emphasis on manual methods
- Identifying individual needs through use of assessment exercises
- Going over material until it has been grasped—mastery learning
- Delivering training in small chunks
- Moving straight from training to application to the job at hand

The above factors constitute guidelines for developing a successful SPC training program. A prototype package—SPC Interactive Training Environment (SPC-ITE)—was developed which succeeds in meeting the above outlined training needs. This prototype consists in a computer package which simulates a manufacturing process. The screen displays a control chart and each time the user presses the space bar a sample is taken and the mean and range are plotted. Fig. 3 (over) shows a screen display after twenty three samples have been taken. The user is able to monitor the process and choose from a range of action options (from the menu bar) which will influence the process in various predefined ways. The particular type of actions available, and the effects they have on the process, can be specified by adjusting various parameters. The process itself can also be tailored to individual training needs, by assigning values to variables such as sample size, product measurement range, standard deviation, and so on. The process can also be set to behave in certain ways. Fig. 4 shows a screen display in which the user can change the specified minimum and maximum values.

The SPC-ITE has advantages over the interactive video used by several companies. It gives the user a more active role, allows training to be related directly to the specific process the trainee will be using, and allows the trainee to take actions and observe effects and benefits of SPC. It also provides a record of user performance (in terms of a quality control rating) and thus allows the user to repeat process runs and try out different actions, noting their effects. The needs which this package does not currently meet are those of providing a general conceptual grasp of the role of SPC, and providing a prior knowledge assessment test. However, these two aspects would be easy to incorporate.

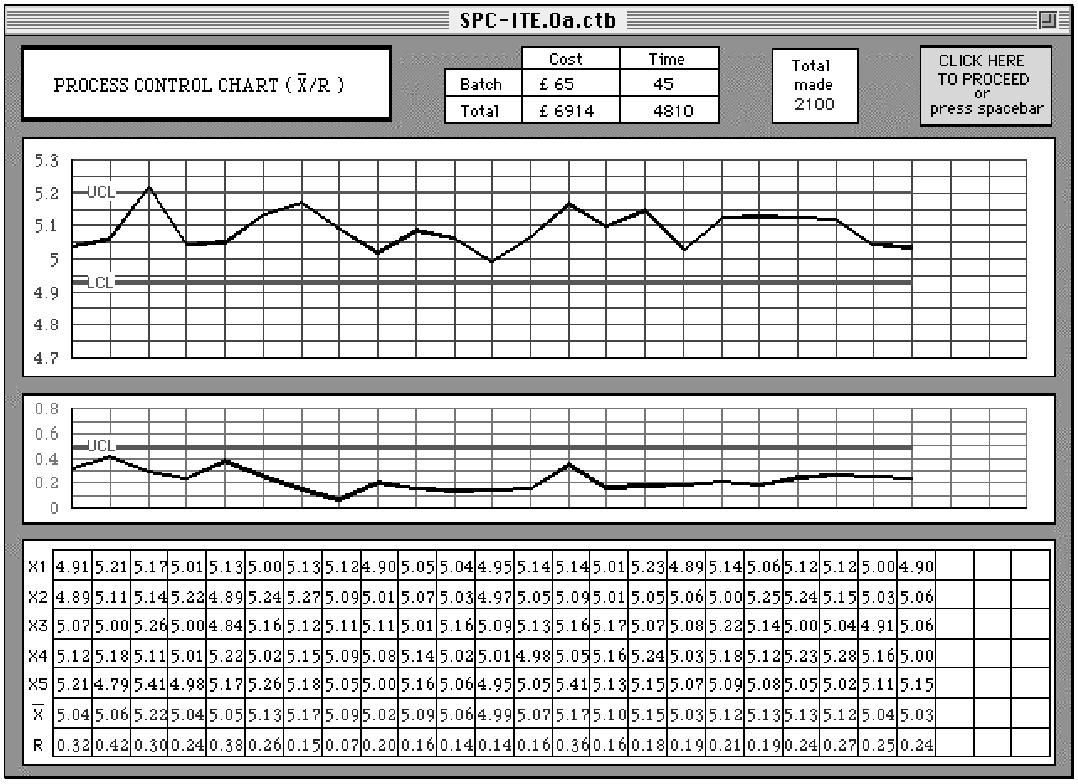


Figure 3: Screen display after 23 samples

The simulator was demonstrated at one company. The quality manager was impressed with the demonstration and made a few comments. He was especially impressed with the way the simulator could be manipulated to relate directly to a specified process. A further comment was that in order to be able to set up the simulator, it would be necessary to approach operators in order to identify particular actions that needed to be carried out in relation to specific processes. Knowledge of these necesssary actions, and details concerning the way the processes worked, was identified as something which tended to be the domain of operators with few other people having much knowledge of these factors. A final point concerning the simulator relates to the level of SPC expertise required to use it. Many of the companies had people running SPC who were not experts in statistics or math. Setting up the simulator itself would involve a fairly advanced grasp of the statistical concepts underlying SPC; thus companies who did not have personnel with this knowledge would need to employ a consultant to help with this.

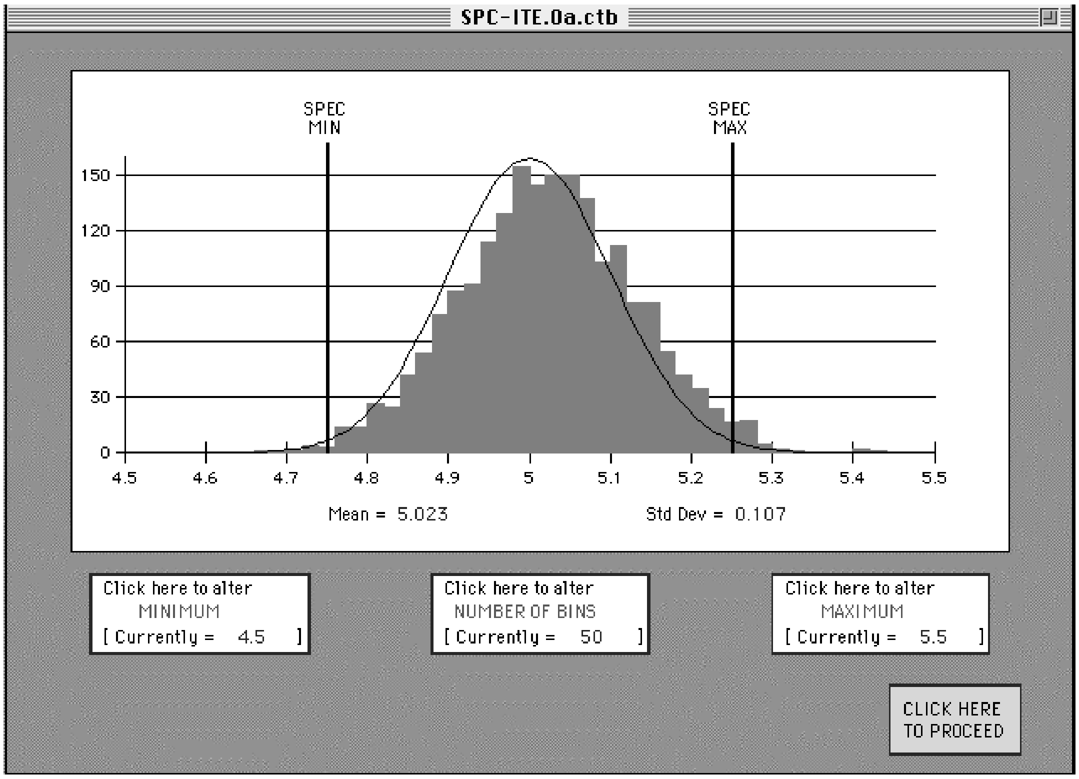


Figure 4: Screen display to change parameters

Acknowledgements

The support of the Economic and Social Research Council for HCRC is gratefully acknowledged. The work was supported by the ESRC, through grant M423284002 (ESRC theme of Innovation, one of two projects on management teams and company innovation).

References

BDA (1992) Why spc: Statistical process control as shewhart intended, booklet no. a4. Tech. rep., British Deming Association.

Cheng, P.-H. and Dawson, S. (1996) A study of statistical process control: Practice, problems and training needs. in press.

Skillman, R. D. (1996) Spc performance: Not what it could have been. *Fastener Technology International*, **February 1996**, 75–78.

Smith, J. (1995) Semi-structured interviewing and qualitative analysis. In *Rethinking Methods in Psychology*. Sage.

Starkey, M. W. (1995) Measurement with meaning: Using statistical process control to improve marketing performance.

Wheeler, D. J. and Chambers, D. S. (1986) *Understanding Statistical Process Control.* SPC Press, Knoxville, Tennessee.

Appendix A: SPC semi-structured interview schedule

- **Business Needs.**
  Background details of the business. Motivation for using SPC. Goals of implementation in terms of business objectives (e.g. reduction of customer complaints, reduction of wastage, etc.).

- **Organisational Levels.**
  Levels in organisation. Functions of levels. Extent of responsibilities at each level. Supervisor/Supervisee hierarchy. General knowledge/qualifications/experience at each level. SPC related knowledge at each level. Computer literacy.

- **Implementation of SPC.**
  In what way and to what extent has SPC been applied? What techniques and tools are used?
  Which levels are involved in the implementation of SPC? What SPC related responsibilities are there at each level?
  Has organisational structure, employee responsibility, etc. changed as a result of the introduction of SPC?

- **Training Needs Identified.**
  Knowledge required to carry out SPC duties for each level. Gap between required and current knowledge.
  Methods of identifying knowledge/skills required. Methods of monitoring the current level of knowledge/competence.
  Variation in needs at different levels.
  Identification of target training population.
  Management attitudes and committment to training. Attitudes of target trainees.

- **Training Given.**

  (a) Material Being Taught.
  Statistical concepts.
  Relation between material taught and application.
  Level of knowledge assumed.

(b) Methods Used.

Classroom or on-the-job? Formal or informal?

Trainers and trainer skills. Course materials/software used. Presentation of training. Length of training. Length of time between training and use. Training methods at different levels in the company.

How is the training assessed for effectiveness? Known but unmet training requirements for SPC. Can staff request further training themselves? Motivation given to employees to accept training/greater responsibility (e.g. higher wage).

- **Success/Failure,**

(a) Of Training.

Methods of evaluating success of training.

Factors affecting success/failure.

Difficulties encountered.

(b) Of SPC.

SPC evaluation criteria?

Problems encountered with SPC implementation.

Benefits stemming from SPC.

Factors affecting success/failure SPC.

Relationship between level of training success and level of SPC success.

To what extent have the business goals and objectives been met?

Appendix B: SPC concepts test

1. What do the following signs mean?

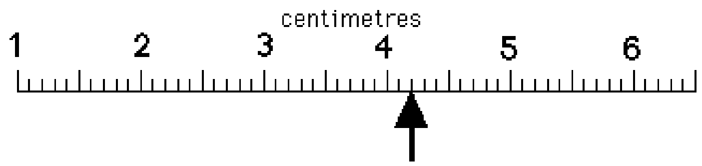
   (a) $+$ Write your answer here ______________

   (b) $\times$ Write your answer here ______________

   (c) $\div$ Write your answer here ______________

   (d) π Write your answer here ______________

2. What is the reading on the ruler at the point shown by the arrow?



   Write your answer here ______________

3. $(4+5) \times (7-2) =$

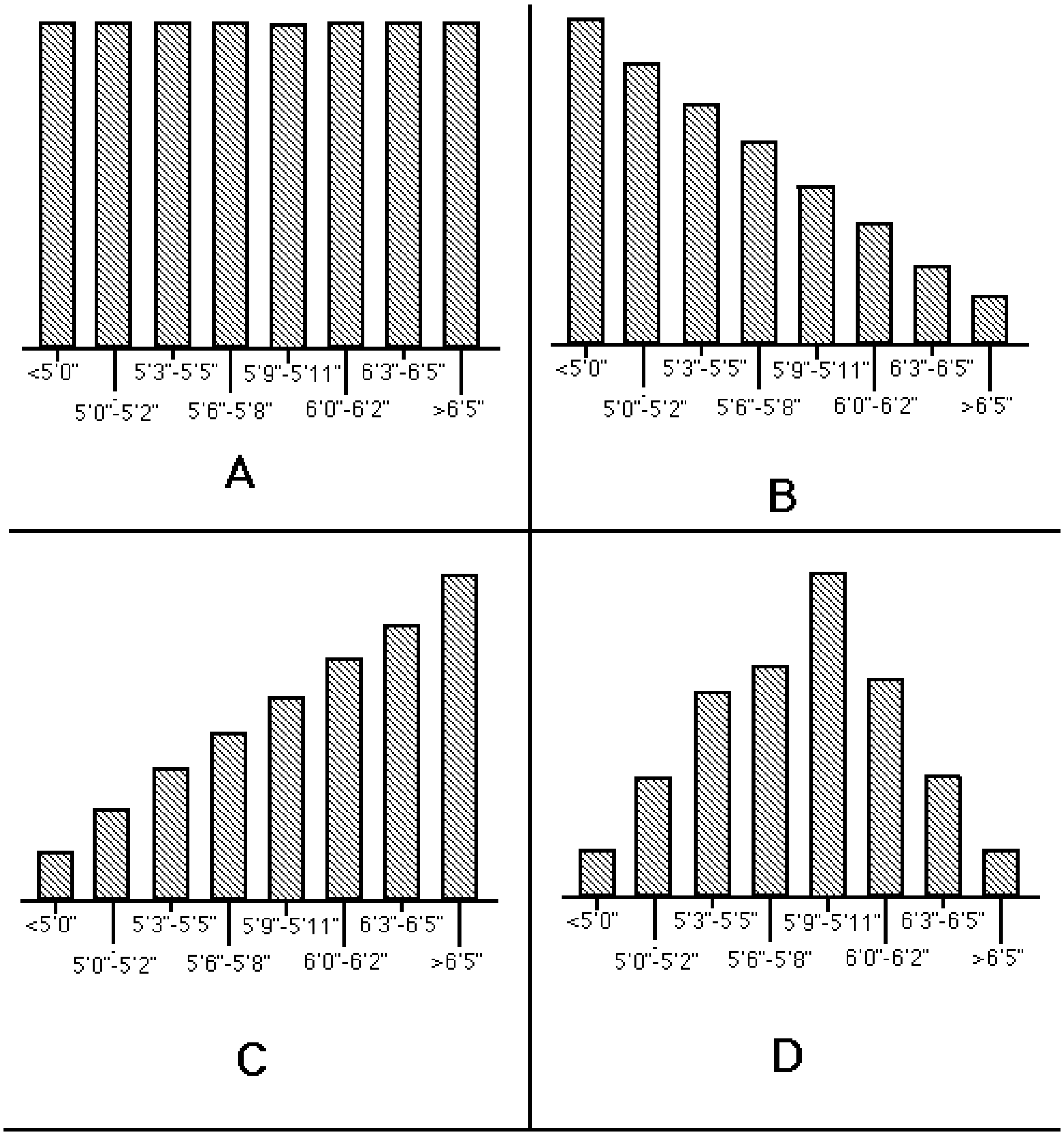
   Write your answer here ______________

4. The number 14 has not come up at all in the last 30 weeks of draws in the National Lottery. The number 34 has come up 6 times. Is 14 more likely to come up in the next draw than 34 ?

   (a) yes

   (b) no

   (c) they are both equally likely to come up



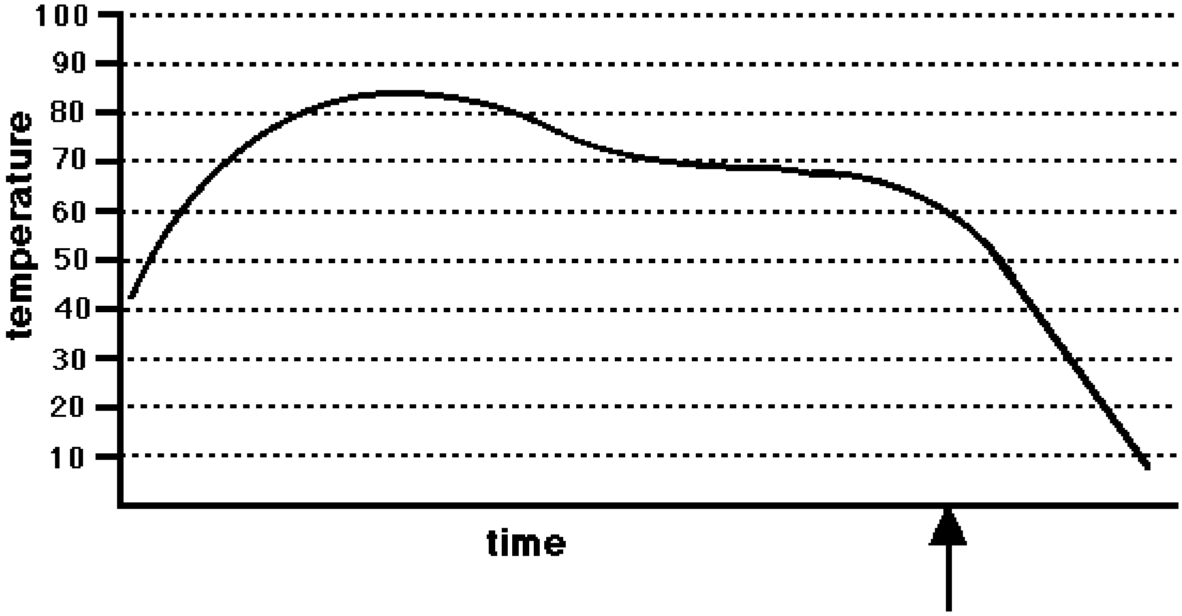
5. A large number of men have their height measured to the nearest inch. They are divided into 8 groups on the basis of their height and the number of men in each height range is plotted. Which of the charts A,B,C and D best shows how mens' height is actually distributed?

   (a) a

   (b) b

   (c) c

   (d) d



6. What is the temperature reading at the time marked with the arrow?

   Write your answer here ____________________

7. Which series of numbers shows more variation?

   (a) 2, 4, 5, 3, 5, 4, 2

   (b) 2, 4, 6, 2, 6, 1, 4

8. A car travels 73 miles in 2 hours.
   What is its average speed?

   Write your answer here ____________________

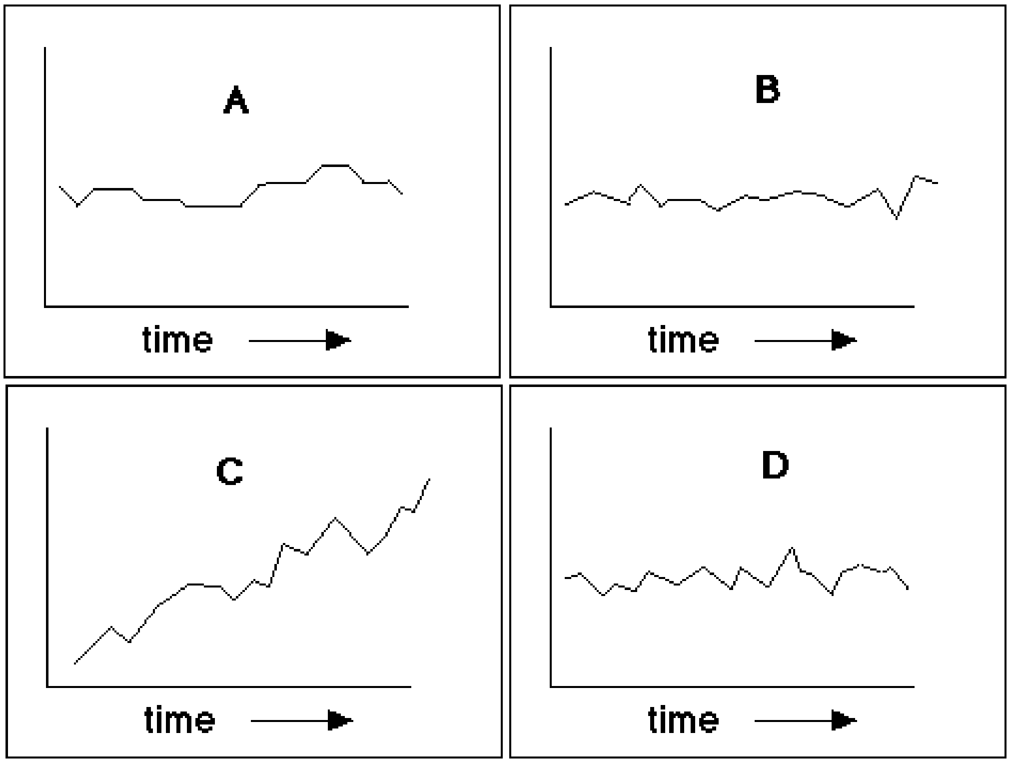
9. If you were asked to collect 10 RANDOMLY sampled products from a production line, would it be better to:

   (a) take the first 10 products that came along the line

   (b) take every 5th product until you had collected 10

   (c) take products from the line at unequal intervals - for example the 2nd,5th,16th,25th,30th, 32nd, 41st,49th,53rd and 63rd products

   Why? Write your answer here ____________________



10. Here are four 'run charts' from a machine that manufactures washers. The graphs show the diameter of sample washers measured at regular intervals. Which chart indicates that there is a problem with the manufacturing process?

    (a) a

    (b) b

    (c) c

    (d) d

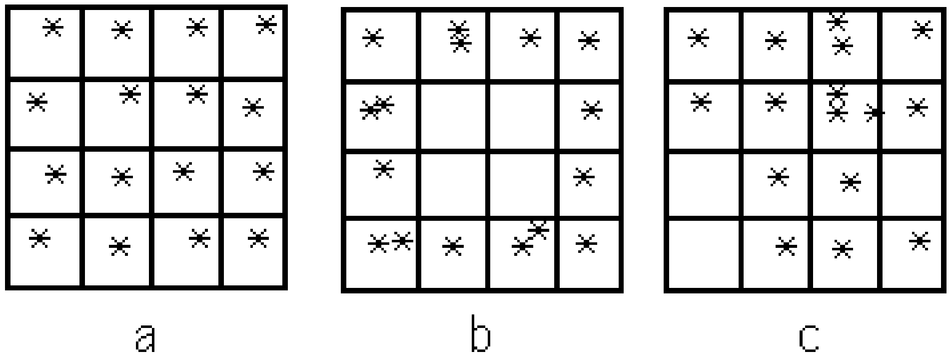
11. The likelihood of a baby being a boy is about 1/2. Which of the following sequences is more likely to occur in having six children?

    (a) BGGBGB

    (b) BBBBGB

    (c) both about equally likely

    Why ? ______________



12. The roof of a small garden shed has 16 square tiles. It begins to snow. After a while, 16 snowflakes have fluttered down onto the roof. The pictures above show three possible snowflake patterns. Which would surprise you least?

    (a) a

    (b) b

    (c) c

    (d) all equally likely

13. Alfred is exactly twice as old as Bill. With the passage of time, will Alfred's age be:

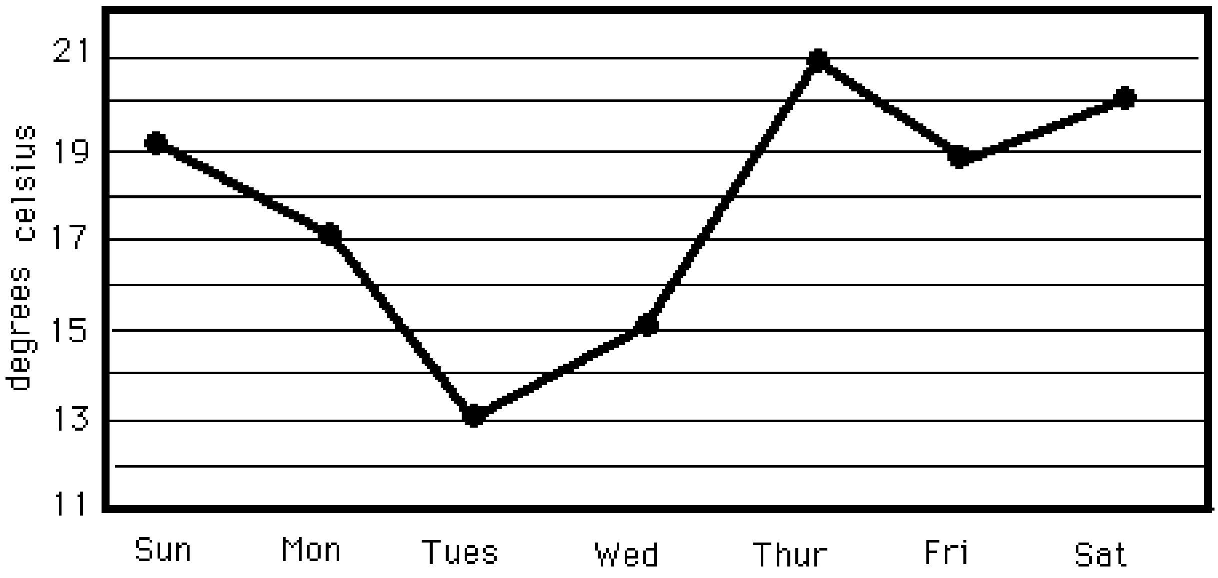
    (a) more than twice Bill's age

    (b) less than twice Bill's age

    (c) remain exactly twice Bill's age

14. The Smith family has 3 girls. What do you expect their next child to be?

    Write your answer here ____________



15. The graph shows the peak temperature recorded every day for one week. On what day was the **MAXIMUM** peak temperature?

    Write your answer here ______________

16. On what day was the **MINIMUM** peak temperature?

    Write your answer here ______________

17. What (approximately) was the **AVERAGE** peak temperature for the week?

    Write your answer here ______________

18. What was the **RANGE** of peak temperatures ?

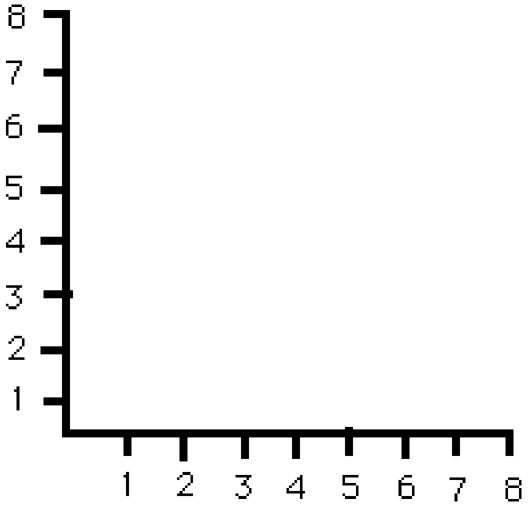
    Write your answer here ______________

Table 10: Average Temperatures in major cities (Fahrenheit).

City	January	April	July	October
Athens, Greece	48	60	81	67
Atlanta, Georgia	42	62	78	62
Beijing, China	25	56	80	51
Buenos Aires, Argentina	63	50	76	60
Cairo, Egypt	70	83	71	76
Chicago, Illinois	20	49	73	54
Dallas, Texas	44	66	86	68
Dublin, Ireland	40	46	59	50
Geneva, Switzerland	34	50	68	51
Hong Kong	59	70	82	77
Honolulu, Hawaii	71	74	81	79
Johannesburg, So. Africa	68	61	52	65
Lima, Peru	74	72	62	65
London, England	40	48	64	51
Los Angeles, California	56	60	71	67
Madrid, Spain	40	54	75	57
Melbourne, Australia	73	58	49	58
Mexico City, Mexico	54	65	64	60
Miami, Florida	67	75	82	78
Milan, Italy	35	56	74	67
Montreal, Canada	13	42	70	47
New York, New York	28	52	76	58
Paris, France	37	51	66	52
Rio de Janeiro, Brazil	79	75	70	71
Rome, Italy	47	57	76	63
San Francisco, California	48	55	62	60
San Juan, Puerto Rico	75	76	80	80
Seoul, Korea	26	52	77	56
Sydney, Australia	72	65	53	63
Taipei, Taiwan	60	70	84	74
Tel Aviv, Israel	57	67	82	77
Tokyo, Japan	38	55	77	62
Vienna, Austria	30	49	67	50
Washington, D.C.	35	57	79	59

19. From the table above, what is the average temperature in Milan in July?

Write your answer here ________________ ____________________________



20. Plot the points (1,3) and (6,7) on this graph and draw a straight line between them.

21. Ruth prefers, when she participates in a lottery, to choose consecutive numbers like 1,2,3,4,5,6. She claims that in this way she increases her chance of winning. On the other hand Jenny claims that the chance of getting six consecutive numbers like 1,2,3,4,5,6 is smaller than that of getting a random sequence of numbers. She says that a lottery is something chancy and therefore there is no chance of getting a sequence of consecutive numbers. What is your opinion with regard to the two attitudes, that of Ruth and Jenny?

    (a) Ruth is right

    (b) Jenny is right

    (c) They are both wrong

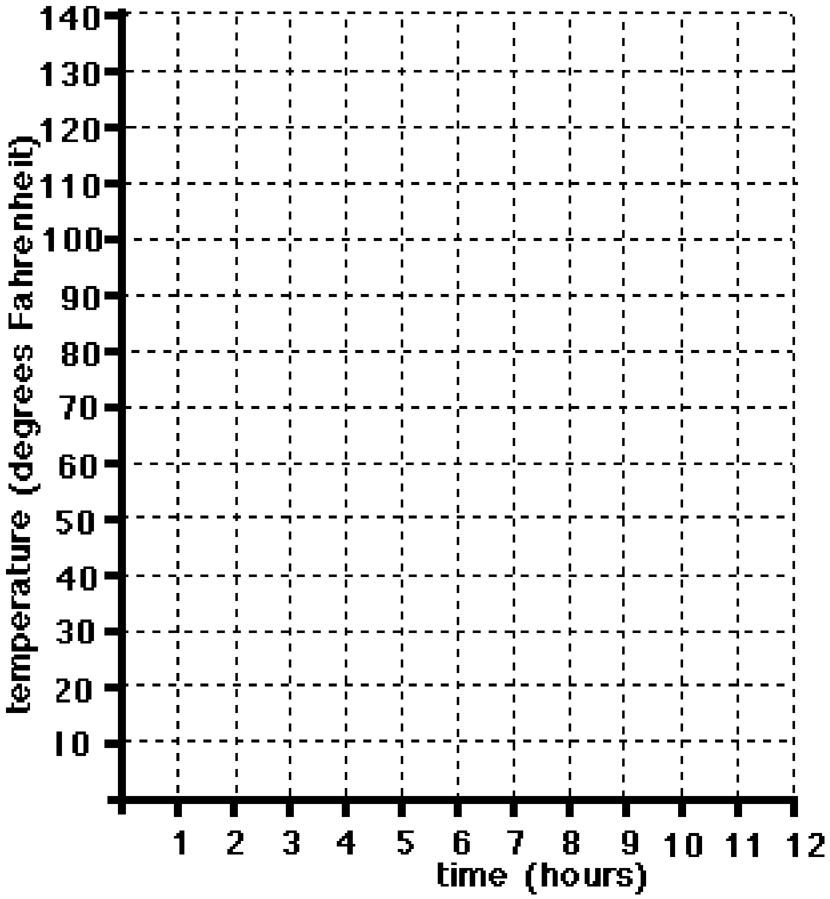
    (d) They are both right

22. A fair roulette wheel has 18 black and 18 red numbers. The likelihood of a ball landing on a red is the same as landing on black. A gambler observes the ball to land on red six times in a row, that is RRRRRR. What do you expect the next colour to be?

    (a) Red

    (b) Black

    (c) Red or black equally likely



23. At 2 o'clock the temperature in a machine room is 60 degrees Fahrenheit. Later, at 10 o'clock, the temperature is 90 degrees Fahrenheit. Mark with an 'X' the temperature at each of the two times on this graph.

Appendix C: SPC test instrument development bibliography

Abele, A. [1989] How to teach statistical concepts to slow-learning pupils. In R. Morris (Ed.), *Studies in mathematics education, Vul. 7: The teaching of statistics.*, Paris: UNESCO.

Eltinge, E. [1992] Diagnostic testing for introductory statistics courses. In F. Gordon & S. Gordon (Eds.), *Statistics for the twenty-first century*, MAA notes number 26, Mathematical Association of America.

Clark, V.A. & Tarter, M.E. [1968] *Preparation for basic statistics: A program for self-instruction.* New York: McGraw-Hill.

Garfield, J. & Ahlgren, A. [1988] Difficulties in learning basic concepts in probability and statistics: Implications for research. *Journal of Research in Mathematics Education*, **19**, 44–63.

Gonick, L. & Smith, W. [1993] *A cartoon guide to statistics*, New York:Harper Collins.

Green, D. [1989] School pupils' understanding of randomness. In R. Morris (Ed.), *Studies in mathematics education, Vul. 7: The teaching of statistics.*, Paris: UNESCO.

Hong, E. & O'Neil, H.F. [1992] Instructional strategies to help learners build relevant mental models in inferential statistics. *Journal of Educational Psychology*, **84(2)**, 150–159.

Krieger, H. & Pinter-Lucke, J. [1992] Computer graphics and simulations in teaching statistics. In F. Gordon & S. Gordon (Eds.), *Statistics for the twenty-first century*, MAA notes number 26, Mathematical Association of America.

Mitutoyo (UK) Ltd. *A guide to the basics of statistical process control*. Mitutoyo (UK) Ltd, Andover, Hampshire, UK.

Moore, D.S. [1992] Teaching statistics as a respectable subject. In F. Gordon & S. Gordon (Eds.), *Statistics for the twenty-first century*, MAA notes number 26, Mathematical Association of America.

Pisani, R. [1985] *Statistics: A tutorial workbook*, New York: W.W. Norton.

Pfannkuch M. & Brown, C.M. [1996] Building on and challenging students' intuitions about probability: Can we improve undergraduate learning? *Journal of Statistics Education*, **4(1)**, http://www2.ncsu.edu/ncsu/pams/stat/info/jse/

Schupp, H. [1989] Appropriate teaching and learning of stochastics in the middle grades. In R. Morris (Ed.), *Studies in mathematics education, Vul. 7: The teaching of statistics.*, Paris: UNESCO.

Shute, V.J., Gawlick-Grendell, L.A., Young, R.K. & Burnham, C.A. [1996] An experiential system for learning probability: StatLady description and evaluation. *Instructional Science*, **24**, 25–46.

Scottish Curriculum & Assessment Guidelines - Mathematics 5-14

Siegel, S. & Castellan, N.J. [1988] *Nonparametric statistics*, New York: McGraw-Hill.

Tversky, A. & Kahnemann, D. [1974] Judgment under uncertainty: Heuristics and biases. *Science*, **185**, 1124–1131.

Yilmaz, M.R. [1996] The challenge of teaching statistics to non-specialists. *Journal of Statistics Education*, **4(1)**, http://www2.ncsu.edu/ncsu/pams/stat/info/jse/