An Interactive VBA Tool for Teaching Statistical Process Control (SPC) and Process Management Issues

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1 Introduction

With a renewed emphasis on managing processes in Operations Management (OM), discussion of Statistical Process Control (SPC) is often included as an integral part of the OM course. Also, what was once thought of as a statistical tool used mainly for production control in manufacturing has now achieved mainstream status in an increasing number of Fortune-500 companies (including service-based).

To assist in the teaching of SPC and business process management, we have developed an Excel VBA tool that can be used in class. The following concepts are explored through guided use of the teaching model:

1. False out-of-control and false in-control indications
2. The role of reduced variability on improved process control
3. Process capability
4. The role of reduced variation in ensuring better process capability
5. Six Sigma
6. Understanding the role and differences between control and specification limits
7. Information from control charts

As we discuss in the next section, this VBA tool can be more than an SPC teaching tool, it can also help demonstrate process management principles.

2 Rationale

With a global emphasis on improved quality, SPC has become a process management tool with renewed importance. Many current business philosophies make specific use of SPC. For example, Just-In-Time (JIT) concepts have become pervasive in business worldwide. JIT espouses SPC as a form of defect prevention. Further, SPC as well as process capability are crucial to the concept of 'Six Sigma' quality programs at global corporations such as GE and Motorola. SPC is also seen as integral to the Total Quality Management (TQM) philosophy and the ISO quality standards. Increasingly, managers must think in terms of processes rather than functions, and a thorough understanding of SPC will be valuable for future managers of processes.

At the same time, in our experience, SPC is also one of the more difficult concepts for students to comprehend. The theory behind SPC is based on probability and statistics, topics many business students are not known to excel in, or have great interest in. Thus, concepts such as process control limits and process capability, often taught back-to-back, are frequently confusing for many students. Similarly, explaining the effect of different z values on errors and the interpretation of sample statistics is difficult without simulating actual process measures. While the issues can be discussed with classical visual aids such as a board or overhead, an interactive computer tool teaches the desired concepts more effectively and quickly.

The SPC tool first evolved from an Excel-based demonstration of how to create statistical process control charts to a VBA-enabled spreadsheet model representing situations of Type I/II errors, and then to its current format demonstrating both process control and capability concepts. The choice of using VBA was natural as the mathematical calculations are handled easily and it allows modifications to be made quickly by anyone with access to Excel on their computer. The graphical demonstration could have been attained with a package such as Macromedia FLASH, but the interactive nature of the tool would have been more difficult to achieve as so much of the graphics are based on user inputs and subsequent calculations.

Many statistical packages, such as Minitab, have the ability to produce a wide array of control charts quickly and easily. While the mechanics of creating a control chart are straight forward, it is important for students to recognize that implementing SPC requires the understanding of the theory behind control charts and the practical implications of that theory. We believe that an interactive visual tool will be much more effective in understanding this concept that relies on a knowledge of probability theory. This tool can also be used to link theory to managerial practice.

3 Previous Work

While interactive exercises in quality control have existed for some time (see Heineke and Meile, 1995, for examples), the use of computer software in teaching is becoming more popular as students' access to software and hardware increases. Many OM textbooks now include a CD ROM with software that can be used to solve problems in a variety of topics and often with graphical and simulation capabilities. Excel-based software is one of the more popular formats because of the ease of use and the availability of Excel. Of interest to this paper are the previous interactive software programs that have appeared in the fields of statistics, decision analysis, and operations management as SPC and process improvement fall under these fields of study.

The topic of SPC is generally dealt with in Operations Management, Decision Analysis, and Business Statistics textbooks. SPC is not usually a topic covered in general-purpose (not business-oriented) statistics textbooks. While textbooks in these three areas cover the basics of preparing and interpreting control charts, only a few (one example is Krajewski and Ritzman, 2002) explain aspects such as the relationship of variance and control limit spread to Type I and Type II errors and other managerial issues. Operations Management textbooks also generally explain process capability through the index formula; however, they do not relate the notion of process capability back to managing the process through process control. In general, the software available with textbooks in the three categories is limited to basic plotting of process control charts.

Advanced quality management and control textbooks often deal with the more sophisticated concepts described above, but these textbooks tend not to include any interactive software. One text that did include a CD-ROM (Summers, 2003) had a limited version of a commercial product with excellent graphics capabilities which allows students to generate various reports. However, it is not well-suited to in-class, hands-on demonstration. For example, it does not generate data to demonstrate in-control or out-of control points (the data set has to be created), nor does it create two overlapping distributions in case of a mean shift to illustrate Type II error or the magnitude of the shift. Thus, the focus is not on the basic principles of SPC and its managerial implications but rather, on control chart preparation and interpretation. Another advanced quality management textbook by Evans and Lindsay (2002) includes only Excel based charts to plot control data.

Statistics textbooks are also available in online or CD-ROM format. Visual Statistics 2.0 (Doane et al., 2001) is an example. Again, the focus in this text is on control chart plotting and interpretation rather than on the illustration of basic principles such the interrelationships between variation, control limit spread and errors, and process improvement.

The student-run website, *www.freequality.org*, has a variety of useful software programs and quality tools aimed at professionals looking for assistance in solving quality and process management problems. These programs would not be effective in the interactive demonstration of SPC and process management.

A search of the *Journal of Statistics Education* did not reveal any article that described software that does what we propose to do in this article. Further, a survey paper by Mills (2002) in this journal categorized the computer simulation methods used to teach statistics. They included areas such as the central limit theorem, t-distribution, and confidence intervals but none on SPC.

Pappas et al. (1982) describe a computer-based SPC teaching tool developed and used in 1980 with their 3rd year mechanical engineering students. They illustrate a teaching tool called PEPEVO that generates process attributes from a normal distribution as well as either gradual or sudden shifts in the process mean. The student can then apply different process chart 'rules' that give an out-of-control indication, such as one point outside the limit or seven successive points on one side on the mean and so on. The user also has the ability to specify other parameters such as the sampling frequency and sample size. The objective is to find the testing procedure that minimizes the cost of the system, including those of sampling, stopping and resetting the machine and the undetected defectives, for the set process parameters.

The focus of PEPEVO is on the design of the sampling system and its implications. Its output includes rudimentary graphics in the form of control charts, but it does not report nearly the same level of interaction as our software. PEPEVO's design is modular and it requires students have the ability to modify the code in order to create new testing procedures and specify processes parameters before running the simulation to view outputs. The authors suggest that its optimal use requires approximately 12 hours of classroom time. The level of technical skill and time required to implement PEPEVO would preclude this tool from use in most introductory Operations Management courses.

In summary, it appears that while software-based SPC teaching tools exist, the focus has generally been on plotting and interpreting control charts. Our focus is unique in that we aim to link control chart issues with their managerial implications. Through this tool, we hope students will attain a better understanding of issues such as:

- *"How does increasing the z-value impact the frequency of unnecessary process stoppages or the amount of time out-of-control processes remain undetected?"*
- *"How does focusing on training employees and better equipment improve the control of the process?"*
- *"What is the difference between a control limit and a specification limit?"*

We believe that the advantage of our software is that these and other SPC managerial issues can be investigated using a single, interactive teaching tool that is simple enough for students to use on their own, or as a guided classroom activity.

4 Learning

An effective teaching tool will help transform business questions into a theoretical framework and then link that theory back into practice. For example, consider the question: *Why does the Type II error decrease with greater shifts in the process mean*? With the click of a button using this VBA tool, students can see that the overlap between the distributions decreases, thus understanding why there is a decreased probability that a sample reading from one distribution will be mistakenly assumed to be from the other. This is the theory, how do we link it to practice? Going back a step, one might ask, "*why is discussing the value of the shift in the mean important*?" Consider a call centre manager who wants to control the mean time that a customer is put on hold. For such a manager, small shifts in the mean and the associated high Type II error may be inconsequential. However, a large shift in the mean implies that customer service has dropped considerably and thus, the magnitude of the Type II error becomes an important consideration when making process control decisions.

Similarly, the tool can be used to emphasize the managerial tradeoffs that exist in process control and process capability. Graphically, is it is easy to see that increasing the sample size results in less distribution spread. Thus the overlap between the sampling distributions is decreased and detecting shifts in the process becomes easier. This strategy however would increase sampling time and costs, and would have no beneficial effect on process capability. Alternatively, a reduction in process variance will also increase the ability to detect shifts in the process while at the same time, improve process capability. Through manipulation of process variables, students will appreciate the positive managerial implications of reduced variance and recognize for themselves how it may be a less expensive long-term option than increased sampling. In practice, reduced variance implies more consistency in the process (process improvement) achieved through employee training, less system breakdowns, fewer mistakes that need to be fixed, advanced technology and the like. This links the theory to practice. Within the JIT context, you have reduced waste and variance.

Consider our call centre manager who wants to ensure that no customer waits more than a certain time. With a graphical tool presenting the process distribution and the waiting time specification limit, it can easily be demonstrated that for a given mean, higher variance/process inconsistency increases the probability of violating this waiting time limit. To ensure that performance goals are met, the process manager could lower the mean waiting time by hiring extra staff, resulting in waste through lower staff utilization. The graphics can also be used to discuss a better option, namely the concept of Six Sigma and how a Six Sigma process is less wasteful and less vulnerable to small changes in process mean.

Thus, we believe that in addition to being a simple quality control teaching tool, the interactive VBA tool also allows the instructor to discuss more general process management principles. Managing processes and their improvement straddles different functional areas such as human resources (employee training), information systems (technology), and accounting (audit). Given that this tool can foster a discussion of process management issues over a wide spectrum of functional areas, its greatest contribution may be made with a more mature audience. We see it as being most effective at the MBA level (it has been tried at the Executive MBA level with good results) or in an elective class on quality management. At the introductory undergraduate level, students may find this a useful tool for them to grasp the more abstract concepts of process distribution versus distribution of sample means, Type I versus Type II error, and process capability.

This tool can be used after the concepts of variation and control limits are introduced. An exercise to demonstrate the concept of variation (the coin-and-tube exercise) can be found in Heineke and Meile (1995). The proposed hands-on activity also assumes a basic understanding of probability distributions and sampling. The interface of the VBA tool invites hands-on exploration of the concepts; its use would be best suited to a lab or classroom with enough computers so that the students can experiment along with the instructor.

5 Using the Tool

Exhibit 1 is a screen print of what the user sees upon opening the VBA spreadsheet. The software allows the user to specify a situation requiring process control. The example shown is from a call centre where the average time a customer is put on hold is measured, but any process parameter may be used by changing the value in the process parameter text box. The screen allows the user to specify two sets of process parameters (both normally distributed for simplicity) through the μ and σ. The software graphs the distributions automatically. The process, as it was designed and set up, is called the *Planned Process*. The second distribution, called the *Current Process*, represents the process as it is actually working. If the process is working as planned (in control), the *Planned Process* and the *Current Process* are shown to be identical (same μ and σ). The TAB key is used to move between controls as is the ENTER key. Exhibit 2 is a screen print of the Process Control Sheet and Exhibit 3 is used for Process Capability issues. The title in Exhibit 1 and Exhibit 2 will state ‘Distribution of Individual Observations’ or ‘Distribution of Sample Means’ depending on whether the sample size is 1 or greater.

The tool actually consists of three parts: this document for the instructor, a Student Lab Manual for students to work through, and the software. The instructor document explains the software and the concepts that can be taught through its use. It is expected that the instructor would be projecting the software image on a screen in the classroom. The Student Lab Manual (Exhibit 4 shows a part of the annotated instructor version) is a detailed step-by-step series of exercises that the students can follow through with the instructor, with space for them to take notes about the results of each exercise and class discussion. The manual and the software may be posted on websites so that students can download and work through them outside the classroom, if necessary. The instructor version of Student Lab Manual has also been prepared where the space for student notes has been filled in with expected results and suggested discussion (shown in bold in Exhibit 4). Since all the documents accompanying the software are in MS Word, they can easily be modified should the instructor choose another example (rather than the call centre) to discuss the process management concepts.

5.1 Process Control Issues

After clicking on the "control" tab, the '*z*' dropdown listbox in Exhibit 2 is used to set *z* to 1, 2, or 3. The Lower Control Limit (LCL) and Upper Control Limit (UCL) vertical lines are automatically generated and shown in orange. Sample size (*n*) may be specified in the given textbox and defaults to 1 if contents are non-numeric or non-positive. If the *n* is 1, the software uses 'Distribution of Individual Observations' as the screen title whereas if *n* is greater that 1, the title 'Distribution of Sample Means' is used. This serves to emphasize that SPC generally uses the sampling distribution. The 'Generate Sample from Current Process' button is used to generate a sample mean from the current process. If the value generated (displayed on bottom right of chart) is within the LCL and UCL, a green dot is correctly placed along the horizontal axis, indicating an in-control reading. If the value generated is outside these limits, a red square is placed, indicating an out-of-control reading. The total number of values generated and the number of these values outside the limits are tallied in the 'total' and 'out' textboxes respectively. By clicking the 'Generate Sample from Current Process' button and then keeping the Enter key pressed down, up to one hundred samples can be generated. This process can also be rapidly simulated by pressing the "Generate 100 Samples" button. The 'Reset' button clears tallies to re-start the sampling process.

5.1.1 False out-of-control indication (α or Type I Error)

Assuming that the process is in control, a false out-of-control indication occurs when the sample mean falls outside of the control limits (indicated by the red square). It can be seen that this will occur about 33% of the time when $z = 1$. Changing z to 2 and then 3 will clearly show that we can reduce the Type I error by increasing z. Students can be asked to repeat the process with various values of n to confirm that larger samples will not help to lower the false out-of-control indication. Thus, adjusting z is the only way to reduce the frequency of Type I errors.

5.1.2 False in-control indication (β or Type II Error)

A false in-control indication occurs when the Current Process is no longer the same as the Planned Process, but the sample indicates that the process is still working as planned. To demonstrate this, set $n = 10$, $z = 3$ and make a minor change in μ for the Current Process. With the process now out-of-control, the sampling would correctly indicate this with a red square, representing the mean, falling outside of the control limits. It can be seen that since the Planned and Current distributions overlap considerably, most readings will fall within the control limits, resulting in green dots (now a false in-control indicator). In fact, with $z = 3$, running a simulation of 100 samples will show that the error rate is almost 100%.

The next step would be to discuss how this error may be controlled. The VBA teaching tool can demonstrate it in three ways:

1. *Reduce z.* This will lower the probability of false in-control. However this will also increase the probability of a false out-of-control (Type I error).
2. *Increase sample size, n.* Since increased *n* reduces sample variance, students will note the narrowing of the distributions and the resulting decrease in the overlap between the Current and Planned distributions. The control limits will also narrow as a result and the probability of a false in-control indication will decrease. Since *n* has no effect on false out-of-control (Type I error), this is a good option. However, it comes at the cost of increased sampling and as mentioned previously, has no benefit with respect to process capability.
3. *Only be concerned about larger shifts in the mean*. By making the Current Process mean significantly differently from the Planned Process mean, it can be shown that the probability of a false in-control depends on how much out-of-control the process actually is.

A combined strategy using the latter two approaches can also be presented -- determine how much of a shift (given the particular example) is enough to cause concern and then choose a sufficiently large sample to reduce the probability of a false in-control reading to an acceptable level. What if the resulting *n* is too large? The next section answers this.

5.1.3 Reduced process variability

The role of reduced variability in improved process control can be demonstrated using the same settings described in the previous section. With the process out-of-control, the σ can be reduced for both the Planned and Current Process, preferably with an explanation about achieving lower σ through better training, more advanced technology, better management, and the like. If one used the coin-and-tube game previously mentioned, one could relate back to this by asking the students to think about how variability could have been reduced, perhaps by using a narrower tube or placing the tube much closer to the target. Students will observe that the two resulting distributions will overlap less and as a result, the probability of the false in-control decreases. Thus, a reduction in variability has the same positive effect on Type II error without the ongoing cost of more sizeable sampling.

It is probably during the discussion of the effects of z on the probability of a Type I or Type II error that the instructor can help students avoid a common misconception. We have often found that when students are asked during exams about the choice of z, they often erroneously state "use $z = 3$ instead of $z = 2$ because it implies better quality control since more sample means will fall within the limits". It is our hope that through hands-on experimentation, most students will avoid this mistake.

5.2 Process capability

The issue of process capability can be explained by using the Specification sheet (Exhibit 3) where the control limits are not shown and n defaults to 1, because process capability is by definition based on individual units. From a customer's perspective, it is the possibility of receiving a defective good or service. The μ, σ, and specification limits can be set by entering appropriate values on the process parameter and specification sheets. While generating units of the product or service, a green dot would indicate a good unit, whereas a red square would denote a defective unit. Initially, σ, the Upper Specification Limit (USL) and the Lower Specification Limit (LSL) can be set such that process capability is low, for example where 15% of the units are defective. By simulating 100 units or observations, students will observe a large proportion of the units will fall outside the USL/LSL. Such a process with high defectives is not generally viable in practice.

Students will also be able to graphically see the negative effect of shifts in the process mean on process capability. As seen in the Process Specification sheet (Exhibit 3), the distribution displayed can be set to the Current Process using the 'Planned Process / Current Process' toggle button. For a given USL/LSL, a shift in the Current Process mean results in the distribution graphically moving closer to the USL or LSL and more units falling outside one of the specification limits.

One method of reducing the defect rate would be to move the LSL/USL farther away from the mean. Students will quickly point out that this does not really solve the problem as it implies lower quality standards. Assuming that the customer is not willing to accept lower quality, how can the situation be improved?

5.2.1 Reduced process variability, revisited

The effect of reduced variability on the defect rate can be demonstrated by going to the process parameter sheet and reducing σ so that the specification limits are close to 3 standard deviations away from the process mean. A few 100-unit simulations will show that less than 1% of units will be defective since almost the entire distribution falls within the USL/LSL. It should be noted that this solution is superior; specification limits have not been changed (implying the same level of quality). Also in many cases, the customer or regulatory bodies determine specifications limits and thus these cannot be allowed to deteriorate.

By reducing the σ further to make the USL/LSL ±6σ away from the mean, the concept of Six Sigma can be explained by showing that the USL – μ = 6σ. One could run a few 100-unit simulations to show that there is virtually no chance of a defective product (even with minor shifts in the mean). It might be useful to point out two aspects of Six Sigma as practiced by organizations. The term 'Six Sigma' as originally coined by Motorola has a slightly different statistical interpretation than 6σ as it allows for 1.5σ shifts in the mean before calculating the probability of an error, which results in 3.4 defects per million. Secondly, it is important to emphasize that Six Sigma in organizations is a process improvement philosophy of which statistical methods are just one aspect (Chase et al., 2004 is an introductory Operations Management text has a detailed section on Six Sigma methodology). To quote former GE CEO Jack Welch (2001), "The big myth is that Six Sigma is about quality control and statistics. It is that – but its much more.

Ultimately, it drives leadership to be better by providing tools to think through tough issues."

5.3 Differentiating between USL/LSL and UCL/LCL

This tool also helps to differentiate between the USL/LSL and UCL/LCL, which is often confusing to students. On the control limits screen, if the n is set to 1, the distribution shown is for individual observations and the option to show the USL/LSL (in blue) on the same graph becomes available. Setting $n>1$ results in the removal of the specification limits, demonstrating that they are not relevant when sample averages are plotted. A discussion of the differences between the two types of limits (control versus specification) as well as the effect of customer requirements on USL/LSL would be appropriate at this time.

To demonstrate the differences, start with a process that is in control (Current Process μ and σ to be the same as that of the Planned Process) set $z = 3$, $n = 1$, and on the specification screen, adjust the specification limits so that they are approximately 1σ from the mean. The instructor should point out that *a sample size of one would NOT typically be used for SPC in practice,* but is required for the purpose of this demonstration only. Returning to the control limits screen and selecting "show specification limits", one can demonstrate how an individual measure can fall within control limits, but still not meet specifications (is defective) since the UCL is outside the USL. Naturally, this situation is not desirable in practice, as it will result in defective products left undetected.

A highly desirable system is one in which the SPC mechanism detects an out of control process long before defectives, as designated by the specification limits, are produced. How can this achieved? This is a good place to reemphasize the attractiveness of Six Sigma. Through process improvement, assume that the σ has been reduced enough such that the USL is 6σ away from the target. When the ‘show specification limits’ is selected in the Control sheet, the USL will fall outside the UCL, which is desirable. To show why this is desirable, shift the current process mean slightly away from the planned process mean. When samples ($n=1$) are generated, indications to stop and correct the process (red squares) should occur before actual defective products are observed, i.e., a warning system. Under a Six Sigma Quality system, it is uncommon for moderate shifts in the mean to result in defective product, and furthermore, these shifts should trigger the SPC mechanism to detect and initiate measures to correct the process.

It can also be demonstrated that control limits are automatically adjusted when one or more of z, n, μ or σ are changed, while specification limits are externally set and thus are not affected by the process parameters. Students should be asked how the specification limits would be set -- in our call centre example, it may be set by management beliefs based on customer preferences. Students will then be able to more clearly see differences between the two types of limits and how each are quite independent of one another. In summary, the UCL/LCL is used to manage the process while the USL/LSL is used to determine whether the product is defective or not – two separate issues.

6 Conclusions

We have presented an Excel VBA tool that can be used to enhance students' understanding of managerial issues in Statistical Process Control (SPC), process variability and Six Sigma. We believe that its ease of use, combined with its graphical interface, make it an effective classroom teaching tool.

The development of the software and manual has been iterative over the past few years and has been based on student and instructor feedback. Colleagues who have used all or part of the SPC tool have felt that it was effective in improving instruction.

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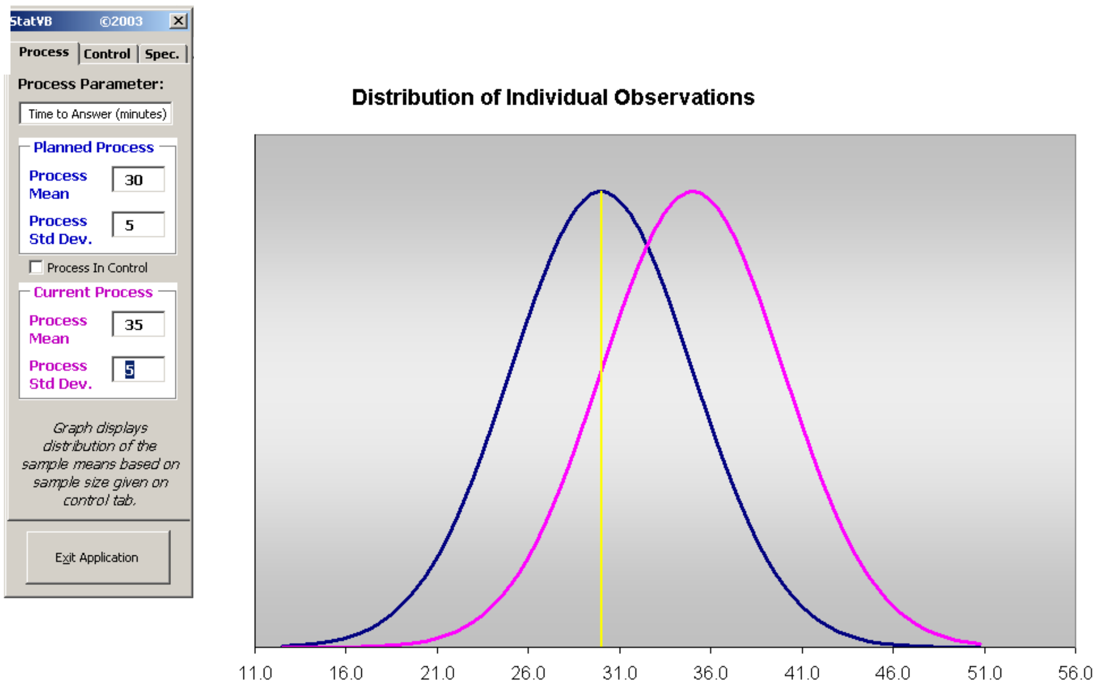

Exhibit 1

Process Parameter Sheet

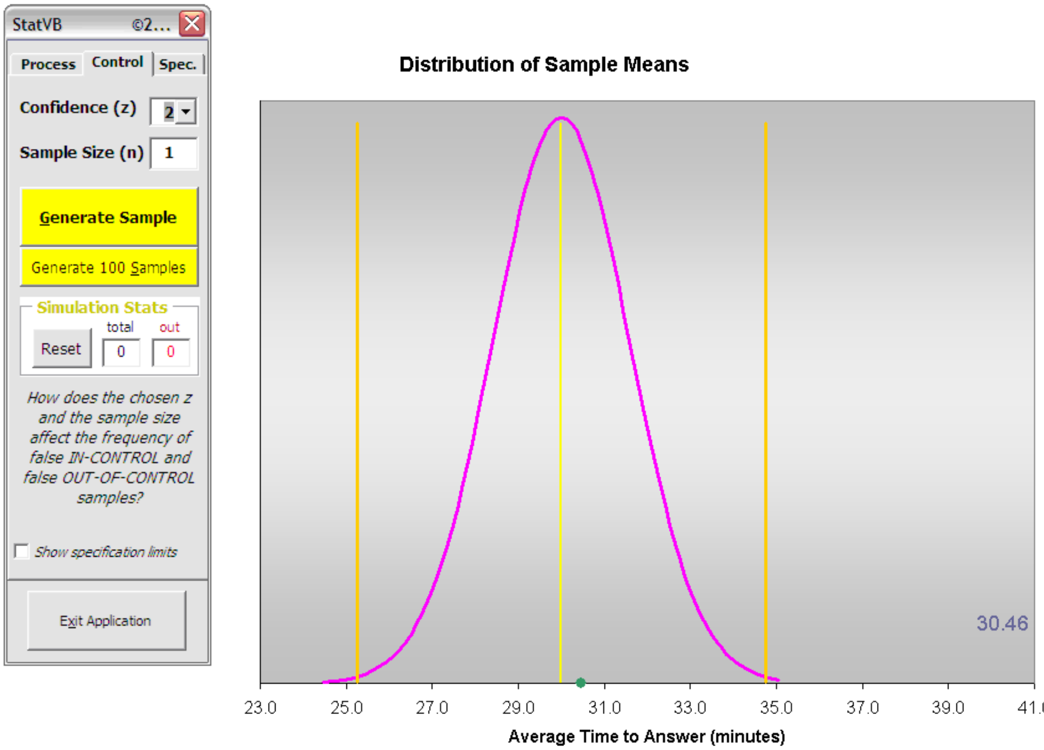

Exhibit 2

Process Control Sheet

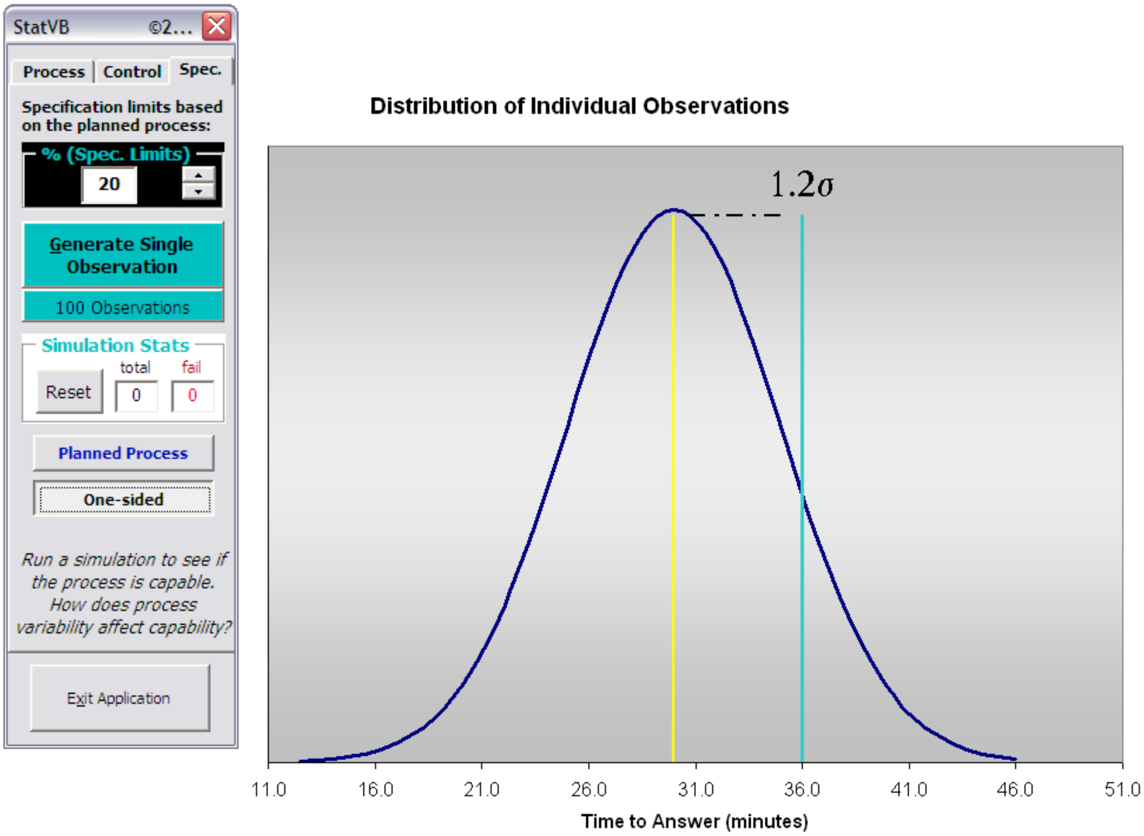

Exhibit 3

Process Specification (Capability) Sheet

Set n = 1, z = 1. Click the *Generate Sample* button. This generates a sample and calculates the sample mean. Since the sample size is 1, the mean is just the individual value. This value is shown on the bottom right of the chart and it is represented as a green dot if within the UCL and LCL and as a red square if outside the UCL and LCL. (*Note: A sample size of one would usually not be used for SPC in practice, but required for the purpose of this demonstration).*

Click it a few more times until you get a red square. In practice, if you were managing this process **what would you do when you get a red square**?

> You would stop the process to investigate the cause of a sample mean outside the UCL/LCL.

Does the call on hold violate company guidelines (defective)?

> Probably not… a red square is displayed if the generated value exceeds 11.5, while it would need to exceed 15 minutes in order to be 'defective'

Exhibit 4: Annotated Student Lab Manual