Teaching How to Calibrate a Process Using Experimental Design and Analysis: The Ballistat

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Abstract

As part of the University of Newcastle’s Total Quality Management (TQM) course, students study Experimental Design (ED) and Statistical Process Control (SPC) within the framework of the scientific approach to process improvement. A sufficient balance of theory and application is required to keep Business and Management students, most with a largely non-quantitative background, interested and aware of the need and method to correctly implement ED and SPC in industry. Tools to facilitate a basic understanding of the importance of the 3Rs, namely, Randomization, Replication, and Blocking, as well as highlighting the potential for mistakes or inefficient calibration techniques are essential in the learning process. This paper describes the use of a particular tool, called the "Ballistat," to illustrate TQM concepts, which enables students to obtain the hands-on experience needed to control processes in industry.

1. Introduction

The scientific approach to process improvement considered in Total Quality Management (TQM) courses, centers on the concept of making data-based decisions (Rao et al. 1996). Accordingly, teaching appropriate methods for collecting valid and reliable data and presenting some simple but useful analysis techniques to facilitate the decision-making process, is required. Experimental Design (ED) is one procedure for actively trying to create information that will benefit an organization and consequently it comprises part of the TQM course. However, as the scientific approach is only one element of the TQM course, and ED is a further subset of the scientific approach, often no more than two three-hour sessions in a twelve-session course is devoted to ED and analysis. Compounding this problem, the students taking the course within the Graduate School of Business are largely from non-quantitative backgrounds. Consequently, it is unlikely for students to get much more than a basic understanding of the principles of ED and some rudimentary analysis that hopefully will propagate further interest in the area.

For students learning ED within the "management framework" of a TQM course, there is a need for the
mathematical rigor behind statistical techniques to be replaced by a more general explanation of ideas and practical application so that usefulness, rather than perfection is exhibited (discussed in Section 6). Tools to facilitate a basic understanding of the 3Rs in ED, not Reading, Writing, and Arithmetic but Randomization, Replication, and Blocking, as well as highlighting the potential for mistakes in industry are essential in the learning process.

There is much educational value for students who are studying ED to be involved in actually designing experiments, rather than simply analyzing the results of an experiment that has already been conducted (Hunter 1977). Interactive sessions that enable students to develop their abilities to apply ED and TQM concepts rather than simply understand the theory are more effective in the learning process than lecturing alone (Britz, Emerling, Hare, Hoerl, and Shade 1997). "Hands-on exercises have proven themselves to be excellent vehicles for communicating and reinforcing the concepts taught in process improvement…and design of experiment courses. This is especially true as related to the planning aspects of data collection and experimental design" (Kopas and McAllister 1992, p.34). Students should be provided with a relatively simple situation (Dean and Voss 1999) in which they can devise an experiment that might provide further insight into the original problem, conduct the experiment, analyze the results and make recommendations that they can then test. "It is now common for students taking a course in experimental design to be required to plan and perform a real experiment" (Box and Liu 1999, p.1).

This paper describes a tool, called the Ballistat, which enables students to obtain the hands-on experience needed to control a simple process. The Ballistat facilitates implementation of the TQM concepts such as teamwork and the scientific approach by requiring students to work together to apply the Plan-Do-Check-Act (PDCA) cycle (Kopas and McAllister 1992; Rao et al. 1996), use some of the seven simple tools of TQM (Rao et al. 1996) and implement the 3Rs of ED. In addition, students gain an appreciation of the need to develop operational definitions (Evans and Lindsay 1999; Ledolter and Burrill 1999) and identify sources of variation in procedures. An analysis of the data using simple linear regression is also suggested. This introduces students to analysis techniques that enable them to obtain a potential solution to their objective, test the outcome on the Ballistat and make further recommendations. Students have found this entire exercise to be a rewarding experience (see Section 4), providing them with a practical application that substantiates the theories learnt. This exercise provides an example of an environment conducive to "memorable teaching" and a "striking demonstration" as theorized by Sowey (1995; 2001).

Having identified the need to provide students with practical exercises to improve their ability to apply TQM concepts, Section 1 describes the aim of using the Ballistat and how it represents a real-life example of a simple process which industries undertake. The second section describes the Ballistat in detail, including its dimensions, operation and availability. Section 3 describes the method of using the Ballistat as a teaching device. It details the task set for the students and the stages through which students should progress during the process of planning, designing and implementing the experiment, followed by an analysis of the data and then "checking" and "acting" on the results. These stages include teams understanding the problem and objectives, planning the process, identifying potential sources of variation, devising and then conducting the experiment, analyzing the data, testing their results, reporting on the ED exercise, implementing SPC and providing future recommendations. Section 4 reports on the results of the exercise in terms of students’ approaches and ideas, the lessons they learn and the general reaction to the whole experience. Section 5 discusses, in the light of ED, a new perspective on "the 3Rs" while Section 6 discusses potential improvements to the experiment and the statistical analyses conducted. The paper concludes with a short synopsis in Section 7 of the Ballistat’s use for developing students’ understanding of the TQM techniques.

The Department has also used the commercially available apparatus called the Catapult (CAT-100) (www.qualitytng.com), which is similar to another device called the Statapult (www.airacad.com/Netscape/Tools/Statapult.html). The catapult is useful in demonstrating the power of fractional factorial experiments to identify the main factors. However, it does not provide an environment to
illustrate how to manage a simple process. Computer simulations, and an apparatus known as a quincunx (www.qualitytng.com), have been developed to illustrate Deming’s Funnel Experiment (Deming 1993) but an environment in which a team was able to calibrate and adjust a process was required to illustrate the well-known problem of "tampering." Hence the Ballistat was developed.

The relative simplicity of the Ballistat having only one predictor, allows students to become familiar with an otherwise complex process, namely calibration and applying SPC to monitor and adjust processes. Additionally, the Ballistat demonstrates the issues of replication and blocking more clearly than the Statapult, which effectively makes use of "pseudo-replications" and balanced designs.

1.1 Aim

The aim of the Ballistat is to provide students with a practical example of working as a team to calibrate a simple process and use the results to monitor and control output. Students will understand the need to flowchart processes and apply Ishikawa diagrams to identify sources of variation, work in teams, develop operational definitions and implement the 3Rs.

The goal is to help students develop their abilities to apply, rather than simply understand, the aforementioned TQM concepts.

1.2 Practical Application in Industry

Calibrating a new piece of equipment so that it produces desirable results is an important process in industry. Failing to understand the existence, and sources, of variation in such processes often results in people tampering with a machine or process. The detrimental effect of such tampering has been effectively demonstrated by Deming’s Funnel Experiment (Deming 1993). Similarly, an inability to implement an effective ED will result in the creation of unbalanced "experiments," obtaining biased data, incorrectly analyzing data and making poor decisions (Deming 1993).

To facilitate problem solving, organizations will often form teams that will then, ideally, take a scientific approach to improve processes. The problem solving process can involve applying many of the seven simple tools of TQM (Fahey and Ryan 1992).

The Ballistat allows students to become familiar with such processes by requiring students to work in teams and implement a scientific approach to ultimately calibrate the Ballistat. Thus the Ballistat is supporting the real-life issues that arise in industry, while strengthening the concepts discussed in lectures. An industrial example is calibrating and controlling a thermostat that keeps a vat of cheese at a constant temperature.

2. The Ballistat

2.1 Physical Description

The Ballistat is shown in Figure 1. It has a wooden rectangular base measuring 1.1 meters long by 14 cm wide by 2 cm thick. A scale (which will be referred to as Scale A) is marked along the length of the base of the side facing upwards with equally spaced increments of 2 cm. Scale A has its "zero" point midway along the base. Secured at either end of the base, and running along its length approximately 2 cm clear of the base, is a metal rod of diameter 1.5 cm. A solid plastic "ball" of diameter 4 cm, with a hollow through it approximately equal to the diameter of the rod is secured on the rod like a bead on an abacus. It is free, with only a small amount of friction, to run along the rod if it is propelled or if the Ballistat is placed on an angle. A groove is carved around the equator of the ball which provides easier measurement of where the ball lies along the scale. A 14 cm metal coil (spring) is fixed about the rod at one end. At the same end as the spring
is attached, there is a 15 cm long wooden lever, or "trigger" positioned to the right of the rod. This lever is slightly hooked at either end. It is screwed, through its pivot point, to a small wooden base that can be moved linearly about 5 cm along a small scale (which will be referred to as Scale B) which runs parallel to the metal rod. Scale B is labeled 1 to 7 in equally spaced integral increments of size 0.4 cm. The small wooden base to which the lever is attached can be fixed in position by a wing nut and screw.

Figure 1. The Ballistat.

From a non-technical, but practical, perspective, compared with other catapult devices the Ballistat is also relatively simple to carry (it can be carried with one hand gripping the metal rod), uses little storage space (either upright beside a cupboard, or horizontally on a shelf with low clearance) and is a complete unit (with no parts that can be misplaced). This apparatus can be operated in a limited area because the ball comes to rest along the rod whereas other catapult devices project the ball to land away from the apparatus. Additionally, this feature is likely to result in more accurate identification of the outcome position compared with trying to record the distance to the first bounce of the ball fired using the catapult. The University made five Ballistats, which have been used during the last six years. Orders can be directed to the designer, Robert W. Gibberd, in care of the author, and cost $AUS450.

2.2 Operating the Ballistat

Ultimately, the lever will contact the ball and as the lever is moved it will force the ball against the spring until such a point that the ball is released and propelled along the rod due to the force of the recoil of the spring. For clarity, the end of the lever that contacts the ball will be referred to as End 1 and the end of the lever that is physically handled by the operator will be referred to as End 2.

Having placed the Ballistat on a level table, the small wooden base to which the lever is attached is firstly fixed in position. The "start" position for the ball requires it being placed lightly against the uncoiled spring with End 1 of the lever on the side of the ball furthest from the spring. Thus the ball is held between End 1 of the lever and the spring. End 2 of the lever is then moved, by the operator, towards the end of the Ballistat that does not have the spring attached. This causes End 1 of the lever to further push the ball against the spring until the lever has moved to a point where the ball is released and travels along the rod, due to the force imparted upon it by the recoil of the spring.

3. Method
The following describes the scenario as presented to the students in the TQM workshop and the intended process students should undertake to advance their ability to understand and implement the TQM and calibration concepts discussed in the course. The process follows the general PDCA cycle associated with the scientific approach. Students’ ideas and comments are not detailed in this section but are provided in Section 4.

### 3.1 Background, Tasks and Objectives

Students are provided with an explanation of how installing and calibrating a new measurement apparatus is an important process in industry. The students are provided with the Ballistat as their apparatus to calibrate. The Ballistat is shown to have only one adjustment mechanism, namely, the location of the lever along Scale B.

The operation of the Ballistat is explained with the objective to determine the position of the lever that results in the ball’s landing position being centered at the "zero" position along Scale A. There is a $10 "cost" for each discharge based upon staff, equipment, overheads and assuming 20 discharges per hour. The proposed budget for providing a solution to the objective is $150.

Having been posed with the scenario, students form groups and attempt to solve the problem. After providing the students sufficient time (given the constraints of the workshop’s duration) to begin to devise their own solutions to the problem, any inadequacies in their suggestions are discussed and, where required, teams are "redirected." Often students will require continued monitoring and assistance, or at least discussion of their ideas with the tutor throughout the process.

The following description of the workshop outlines the procedure as it may be conducted if a team were correctly employing the techniques discussed in the lectures. This is the model the tutor may use to facilitate the students’ learning process.

### 3.2 The Forming Stage - Team Roles and Goals

The role for each of the team members and the team’s objectives should be clearly established by each team to ensure everyone is aware of how they fit into the process and that there is a common goal. Such roles include, but are not necessarily limited to, the leader who directs the group towards their objectives, the facilitator who assists in the group’s discussions and a scribe to ensure efficient documentation of the process. The roles when conducting the experiment would be defined during the "planning" stage. The team should then create a quasi mission statement to ensure that the team members have a clear and common focus. An example may be:

"To work as a team to apply a scientific approach and create and conduct an experiment in order to determine the position of the lever on the Ballistat that will result in the ball landing, after having been discharged, on average, at the zero level."

The goals of this study may be achieved by using the following steps:

1. examining the apparatus and establishing any assumptions;
2. planning the process the team will follow;
3. designing the calibration experiment;
4. conducting the calibration experiment;
5. analyzing the data;
6. checking the results;
7. making recommendations.
3.3 The Planning Stage

Ballistat Assumptions

Having examined the Ballistat, students may need to make certain assumptions before designing the experiment. Such assumptions may include that the zero level for the output is achievable, that the position of the firing mechanism is indeed a predictor of the outcome and that there exists an optimal position for the trigger that more consistently obtains the required output.

Planning and Documenting the Process

The teams are required to document the process and begin by constructing a top-down flow chart of the process that the team will follow. The students will modify their original chart as they develop their methods, resulting in a final top-down flow chart like that in Figure 2.
Form the team
- Determine roles (scribe, leader, facilitator)

Determine team’s objectives
- Identify the team’s primary goal
- Identify possible subsequent team goals

Assess the apparatus
- Inspect the Ballistat
- Establish its operation
- Identify assumptions

Plan the team’s process
- Flowchart the process (design a top-down flowchart)

Design the Experiment
- Use Ishikawa diagram for sources of unwanted variation in output
- Establish standard operating procedures (SOPs) (discharging, measuring)
- Incorporate replication and randomisation
- Block on factors of no interest
- Assign roles (those who will measure landing position, discharge Ballistat)
- Determine method to assess reliability of the process

Pilot test the Experiment
- Ensure everyone is clear on their role
- Implement the SOPs
- Run a few trials to determine that the zero output is achievable
- Learn from trials
- Modify ED as applicable

Execute the Experiment
- Learn from the pilot test
- Ensure everyone is clear on their role
- Implement SOPs

Collect the results
- Record manually and independently by two people.
- Enter both sets of results into the computer

Analyse the results
- Apply regression to obtain optimal lever position

Test the results of the analysis
- Consider the variation inherent to the Ballistat
- Construct control limits using the estimated process’ variation obtained from the regression results
- Repeat discharging at the proposed optimal lever position

Make recommendations
- Comment on variation in the process and the equipment
- Discuss methods of analyses
- Identify possible improvements
- Discuss methods for monitoring and adjusting the process in the future
Designing the Experiment

Teams need to establish the role each member will play in running the experiment and collecting the data. This involves establishing the positions required to be filled and whether team members should exchange roles throughout the experiment.

The positions to be filled include:

- operating the lever that discharges the ball on the Ballistat;
- setting the position of the lever, along Scale B, for each run (possibly two people for verification);
- measuring the position of the ball after being discharged (two people independently measure and manually record results to later enable an assessment of the reliability of the measurement process);
- ensuring the Ballistat is in the same position (slope, etc) before each run;
- entering data into the computer.

Teams may consider other potential areas requiring work such as whether there needs to be a position filled that ensures the rod is clean and free of dust. A discussion on the possible rotation of roles in the experiment should be instigated here. Issues such as the number of people who should fire the Ballistat should be considered and lead to the discussion of potential sources of unwanted variation and how one might block on such variation.

The potential sources of unwanted variation in the output (that is, the ball’s landing position) can be identified and considered via team brainstorming and implementing an Ishikawa diagram like that in Figure 3.
SOPs are required to standardize all operations in order to decrease variation in procedures and allow for repeatability of the experiment to produce reliable results. Procedures that require operational definitions include how to:

- discharge the Ballistat (teams will consider methods such as a quick flick of the lever to release the ball or moving the lever with a constant, smoother action through its arc);
- align the lever mechanism on Scale B (determine with which side, or in the middle, of the thickness of the marked scale to align the mechanism);
- measure the output’s location on Scale A (measuring at the middle or either end of the ball; accuracy of interpolation between scale markings);
- position people measuring the output (reduce error resulting from parallax that occurs when a person is measuring from an incorrect position, or bumping the Ballistat when trying to measure).

All roles should be clearly defined such that any team could repeat the experiment and have comparable results. This shows the required planning in what seems a rather simple procedure.

Given the cost constraints, 15 experimental runs can be afforded. Although a linear relationship is being assumed, students should have the opportunity to assess the relationship between the ScaleA_Reading and ScaleB_Position using a correlation coefficient and scatterplot (one of the seven simple tools of TQM (Rao et al. 1996). Using two or three levels may obscure a potential non-linear relationship. Additionally, to measure the within-level variation, that is, the variation in the outcome for a given value on Scale B, one or two replications at each level is inadequate. Thus, to ensure replication at each level and consider non-linearity, four levels will be used with each having three replications. There are a number of combinations of levels and replications possible, which can be considered by the team. However, it is intended that the experiment consist of three replications at each of the 1, 3, 5 and 7 levels.

Students become familiar with the equipment and their process over time. Initially, there is a lot of variability in their process, whereas later they understand the process. Accordingly, if they ran the 3 repetitions at level 7 first, followed by 3 repetitions at level 5, and so forth, a "learning effect" may be introduced, thus biasing the results. To ensure that such changes in conditions over time do not affect the outcome, three "blocks" of four runs are created, ensuring that for each block, each of the four levels (1, 3, 5 and 7) is observed and within each block, the time order of the observations at each level is randomized. Note that randomization alone of the entire 12 runs could still yield 3 repetitions at level 7 first, followed by 3 repetitions at level 5, and so forth, thus blocking is an important part of the ED.

A pilot sample of three runs can then be incorporated to verify that output both above and below zero is achievable. These values can then lend support to the selection of levels at which the lever will be located. The lever will be positioned at the minimum, median and maximum settings for the pilot sample; specifically, positions 1, 4 and 7, on Scale B.

This completes the "Plan" stage of the cycle.

### 3.4 Implementing the Experiment

#### Data Collection

The "Do" stage begins with the team members adopting the SOPs, undertaking their roles and running the pilot study. The results indicate that output above and below the desired zero outcome is possible (see Table...
Accordingly, although limited data, they support the notion that the proposed experimental levels are practical.

**Table 1.** Results of the pilot sample.

| Scale B Reading | Scale A Reading |
|-----------------|-----------------|
| 7               | -6              |
| 1               | 6               |
| 4               | -1              |

The experiment is then conducted using the randomly ordered levels determined in the planning stage (see Section 3.3), and the results are obtained. Two people independently record all the landing positions for the ball to allow an assessment of the validity and reliability in the measurement process. However, only one set of readings is presented in this paper. The data are presented in Table 2 for the twelve runs of the experiment in the randomized order in which they were conducted.

**Table 2.** Predictor and outcome readings from the Experiment.

| Scale B Reading | Scale A Reading |
|-----------------|-----------------|
| 7               | -8.5            |
| 5               | -4              |
| 1               | 8.5             |
| 3               | -3              |
| 5               | -0.5            |
| 7               | -9              |
| 3               | 4.5             |
| 1               | 13.5            |
| 3               | -3.5            |
| 1               | 12              |
| 5               | -3.5            |
| 7               | -10             |

**Method of Analysis**

The data are then plotted and a simple linear regression analysis is conducted. The resulting linear equation is ScaleA_Reading = 12.408 - 3.175(ScaleB_Position). This is then used to find the lever position that results in the outcome being zero. Thus for this data, the predicted position for the lever is 3.91 (that is, 12.4083/3.175). The advancement in knowledge resulting from the "Do" stage of the PDCA cycle now needs to be checked.
3.5 Testing the Results

To check the results of the analysis, the lever mechanism should be positioned at 3.9 on Scale B and the students allowed to check the outcomes from repeated discharging of the Ballistat. Students can then begin to appreciate the amount of natural variation in the process as well as verify that this position does result in achieving the experiment’s objective.

At this stage, the students should consider methods for the future monitoring of the process and assessing the natural level of variation in the process via control charts. The mean squared error calculated from the regression analysis should be used to estimate the process’ variation and create upper and lower control limits. The students can then chart their results obtained during the "check" stage and begin to monitor the process.

The "costs" associated with this "check" stage may be worth incorporating in the original budget, such as an additional $40 earmarked for confirmation runs. However, an "income" obtained from producing desirable output may also be included in the original scenario provided to the students, which may offset such costs. This is discussed further in Section 6.

3.6 Recommendations

Having conducted the experiment and checked the results, the "Act" stage involves the students documenting their findings and assessing the Ballistat. Issues regarding the level of accuracy of the measuring process (such as the precision of the scale used), improvements required in the SOPs and the need to use an effective scientific approach, should be discussed. If time permits, the students should then begin to develop an algorithm for making adjustments to Scale B based on future runs and the corresponding control chart. This enables students to obtain a feel for reporting on their own findings and suggesting improvements to a process or an instrument (in this case the Ballistat) rather than accepting the status quo.

4. Results from the workshop: Students’ ideas

The decision process of students during the workshop exhibits the need to reinforce TQM concepts with practical examples. Issues such as pilot testing, randomization, replication and blocking and most calibration concepts, although discussed and agreed to be clear to the students in class, require the opportunity to be implemented to increase comprehension. The Ballistat facilitates this learning very effectively.

The methods that students use to calibrate the apparatus are often interesting. Some students have occasionally obtained a zero value in their first or second discharge and quickly discarded the notion of variation, immediately believing that they must have found the answer. Others haven’t necessarily landed exactly on zero, however, the one-off "near-zero" outcome has prompted them to believe they must be near the correct level on Scale B. Students have also proposed testing two values on Scale B and having seen their outcomes on Scale A, then move the Scale B back and forth the remaining ten or so runs, believing they will home in on the correct position.

Questioning the students on how they intend to react if they see a particular outcome, given the aforementioned proposed methods, is often required. For example, if the ball lands at +7 on the large scale, what will they do? Replies are commonly to suggest that the lever’s position needs to be altered. If asked what they would do if the ball lands at -2, students are a little hesitant, however, still suggest a "minor" adjustment should be made. When asked how they would react if the ball lands exactly on zero, replies have included leaving the lever in that position or repeating the process at that level to verify. Aha! So now
they want to have some repetitions! When questioned as to why they want to repeat the process students have then alluded to the variation in the process, wanting to "make sure it is correct." Many students at this point in the workshop have recalled the issue of variation and understand what is potentially wrong with their methods. They begin to identify the within-level variation. Additionally, they recognize that, as the within-level variation hadn’t been considered, continually altering the setting after each discharge is possibly a reaction to natural variation.

Discussing this issue with the students, pointing out how we’ve established that there is variation in any process and that this resulting zero, or near-zero, outcome may in fact be an extreme in the tail of the distribution for the current position of the lever, is rather enlightening. A diagram such as that shown in Figure 4 is often helpful to accentuate such issues. It heightens their recognition of the need for replication and an assessment of the process’ natural variation.

![Figure 4](image.png)

**Figure 4.** Exhibiting uncertainty in the distributions of landing positions for a given lever setting.

Asking what the distinction is between an observational study and an experiment can then follow. Students will often reply "randomization" or "the 3Rs." They are then heading towards conducting an effective experiment.

The method of analysis to obtain the desired level at which to position the lever is another source of edification for the students. It is often their first application of what, to many, is seen as one of those techniques that statisticians use to equate "y" with "x." However, the reactions to seeing how the data collected from their experiment is then going to be analyzed (by them!) to provide a solution to their original problem is a delight to many students who see the practical use of this technique.
5. Relearning the 3Rs

As Sowey (1995; 2001) explains, part of effective teaching is making it memorable. With the many new concepts that students need to learn it can be beneficial when a useful analogy or "retrieval cue" (Myers 1998, p.289) is available that can assist memory retrieval. In the instance of ED, the proposal is the 3Rs; not Reading, Writing and Arithmetic but Randomization, Replication and Blocking.

Students need to remember these fundamentals and will often recall "that 3R thing" from the lectures associated with ED. And with little, or no, prompting they then proceed to recall each part of what "that 3R thing" refers to and how and why each of the concepts is used.

6. Further Recommendations

It is apparent that there are various shortcomings in the methodology such as assuming a linear relationship between the lever position and the landing position for the ball. However, the point of the experiment is to provide a useful application for these students on how to apply ED and implement regression techniques, rather than focus on potential non-linear relationships. Nevertheless, it is noted in the workshops that the relationship is not truly linear, due to the spring involved and that a more precise relationship may exist. Additionally, the balance between measuring the amount of within-level variation and identifying the linear or non-linear relationship between the predictor and outcome, given the cost constraints of the experiment, are issues that the class should consider when establishing the numbers of levels and replications.

There are neither sophisticated tests of significance nor residual plot analyses to test for the assumptions of the simple linear regression. Again, students of the TQM course must be made aware that such tests do exist and that students are simply being introduced to regression. Otherwise their ignorance of more advanced Statistics may lead them into a false sense of knowledge. More sophisticated audiences with greater exposure to regression theory may like to incorporate such ideas.

Further improvements to the experiment may include allowing a greater number of replications, which may also enable the non-linear relationship to be more readily visible when accompanied by a residual plot analysis. Additionally, the future monitoring of the process via control charts can help assess the level of variation in the Ballistat and decisions could be made regarding improvements to the Ballistat. Students should also include in their report a comparison of the two readings made by the students and whether more precise scales should be used, or whether an improved method of measuring is achievable to ensure the reliability of that procedure.

Classes that have sufficient time might allow the students to use their own methods to obtain the optimum position. Students can be encouraged to modify the lever position intuitively, making use of the continuous nature of the lever position along Scale B rather than using "levels," without using control charts and to compare the efficiency and results with that obtained when implementing the design offered in this article.

The introduction of acceptable tolerance limits has also been incorporated into the workshops that our Department have conducted. For example, students have been given the criteria that if the ball falls within 0 ± 2 on the scale, the product is suitable for sale at a price of $15. Otherwise it is a defective item and is destroyed. This can make for interesting decisions, once it is recognized that there is money to be made that can offset the costs of experimentation and "confirmation" runs. Future monitoring of the process can then also incorporate an analysis of profits. Alternatively, an additional budget for the checking stage may need to be initially specified.

Introducing specification limits also allows capability analyses to be considered. However, minimizing a Taguchi Loss Function (Rao et al. 1996; Evans and Lindsay 1999) is an even better approach.
7. Epilogue

The TQM course is not designed to create statisticians. The "statistical" section of the course includes the provision of certain simple yet powerful methods of collecting and using data and increasing students’ awareness of techniques that can be implemented so that they may recognize situations where these techniques are useful. Their knowledge can then motivate further learning or employing the skills of someone with a sufficient level of statistical background.

The paper has described the apparatus known as the Ballistat and how ED, regression and SPC principles are used to calibrate and monitor an industrial process. Students also experience teamwork and other concepts taught in the Graduate School’s TQM course for Management and Business students. However, it should be evident how it may be built upon and used for students with higher levels of quantitative and statistical skills.

It has been found throughout the numerous workshops in which this exercise has been conducted that it has helped students to retain ED and TQM concepts and increases their enthusiasm towards what would otherwise have been theory. This retention and understanding of the concepts is evidenced in exams where students are consistently able to describe the 3Rs and their application to ED. Students have freely commented at the conclusion of the workshop and at the completion of the course that the Ballistat experiment was a very useful application which reinforced the ideas underlying ED and process control.

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