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Teaching Statistical Quality Control by Applying Control Charts in the Catapult Shooting Experiments

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1. introduction

In today's highly competitive business environment, high quality products and services are necessary [1]. Statistical Quality Control (SQC) has been widely accepted as an important concept in manufacturing engineering curriculum. Introducing SQC to the manufacturing students provides them with a comprehensive education in total quality management philosophy, preventive process-oriented methodologies, and planning, control, and improvement techniques[2].

At our university, Statistical Methods for Quality Improvement (MFG 333) is a junior-level course offered to the students majoring in Manufacturing Engineering Technology. The topics of this course include the strategies for continuous manufacturing process improvement, graphical and numerical methods for data analysis, methods for manufacturing process control and acceptance criteria. After successfully completing the course the students are expected to:

- understand and practice the basic concepts and principles of quality improvement techniques, control charts for variables, control charts for attributes, acceptance sampling systems, reliability, total quality management, ISO-9000 quality system, 6-sigma concept, etc.
- identify engineering problems related to the production of goods and services.
- measure, evaluate and improve production processes and systems.

2. issues in teaching the course

Like most engineering instruction, an SQC course is still being taught in a lecture format [3]. The primary functions of the faculty member in this teacher-centered approach are to lecture, give assignments and tests, evaluate student performance and assign grades [4]. While lecturing is an excellent method of communicating large amounts of information, students are experiencing passive learning and the learning effectiveness is often small [5].

A student-centered, project-based learning approach needs to be established to improve the teaching of MFG 333. In the student-centered environment, learning is often facilitated through active learning. The faculty member should actively involve the student in the learning process (besides the functions conducted under a teacher-centered approach). The active learning occurs when the students do more than listening during class. It is accomplished through challenging the students to ask and answer questions, engaging students in small-group discussions, and incorporating problem solving and projects into the course [6].

Several universities have started building a student-centered environment when an SQC course is taught. University of Nebraska has developed a catapult project to help the students learn the concept of variation [6]. Miami University has provided labs in which the students use optical comparator, electronic calipers, image analysis system and hand tools to strengthen the understanding of total quality management [7]. University of Texas - Pan American has implemented a web-based Mouse Factory lab to address the quality competency gap in the use of control charts for variables. In this lab, the students can go on-line to generate their own control charts and evaluate the effectiveness of their control charts upon the number of good parts produced and the defect rate [3]. However, there has been no report so far that a simple hands-on experiment has been designed to help the engineering students apply the control charts in the SQR course.

3. design of the catapult experiment

The catapult project simulates the manufacturing improvement process. It uses a catapult to simulate a production process and a target board as product specifications. As the major shooting equipment in the experiment, the catapult is shown in Figure 1 (a). The projectile is either a tennis ball or a golf ball as shown in Figure 1 (b). The target board is made of plastic foam. It has 3 concentric circles. The largest circle has the diameter of about 1 foot (as shown in Figure 1 (c)). The second circle is 8 inches and the third circle is 4 inches in diameter. As illustrated in Figure 1 (c), there are 4 zones on the target board. Zone 3 is the smallest area and is the target that the projectile aims at. Zones 2 and 1 mimic the deviation of the product quality from the specifications. Zone 0 represents a failed catapult shooting – a process failure that produces scrapped products. The lab accessories include a tape measure, a ruler, a couple of C-clamps, cushioning materials and duct tapes.

(a) Catapult.

(b) Projectiles (a tennis ball and a golf ball).

(c) Target board.

Figure 1. Catapult and projectile used in the project.

During experiment, the projectile is fired at the target. If the ball hits Zone 3, a score of 3 will be given. If the balls hits Zone 0, the score will be zero. The goal is to let the ball land in Zone 3 each time it is shot. After the data of 100 shots are collected, the students are expected to use the formulas introduced in the SQR textbook [8] to create control charts (X-bar and R charts) by calculating the upper control limit, lower control limit and mean value. They also need to do the analysis on the outliers or patterns of the control charts to identify assignable and unassignable causes.

After the initial data collection and analysis are done on the control charts, the students will start making improvements to the shooting process. They can change any configurations of the system. They can change the projectiles, shooting angles, location of tension pin, shooting cup positions, catapult fixtures, cushioning materials, and shooting distances. Then, they will conduct another round of experiment. Data are collected and control charts are drawn and analyzed again.

By using the information provided by the control charts, the students are able to identify the most significant factors that may help increase the accuracy and preciseness of the catapult firing. The students will put these factors together and form a standard procedure to improve the process in their future launches. They will continue the experiment for several other rounds to see if the process can be steadily improved. In each round, the students are required to follow and continuously update the standard procedure. (Please note that this approach has been proved to be an effective quality control method by Professor Masaaki Imai in his book *Kaizen – the Key to Japan's Competitive Success*, ISBN 0-07-554332-X, copyright 1986, McGraw-Hill Publishing Co.)

After the catapult system is in control and its performance has become reasonably good, the students can go head to reduce the diameters of Zones 1, 2 and 3. They will repeat the steps described above until the best performance of the catapult system is achieved.

In the next section, the exemplary activities of the students will be described in details to illustrate how the catapult project was implemented.

4. implementation of the catapult experiment

The students started the experiment by building the run charts. The hardest launch was the first one and once it was done, the other launches were easier. The students brought in a drafting compass and a Sharpie marker and made a bull's eye target on a plastic foam board. The catapult was placed about 13 feet from the target. In order to catch the ball easily, one group of students put a round oatmeal can horizontally on Zone 3 as shown in Figure 2 (the can is in the upper left corner). The students fired the first 100 shots. They eyeballed the results and recorded them on a sheet of paper.

Figure 2. The catapult and the target (with a can to catch the ball easily).

During the experiment, the students found out some effective ways to collect data. As one student put in his lab report, “we had a great idea to use carbon paper to help identify the location of the hits. We did learn that the person operating the catapult is basically only seeing the trajectory in 2 dimensions from behind. Observers at a 45° angle have a better perspective to judge the impact point.”

The initial control charts generated by the students are shown in Figure 3.

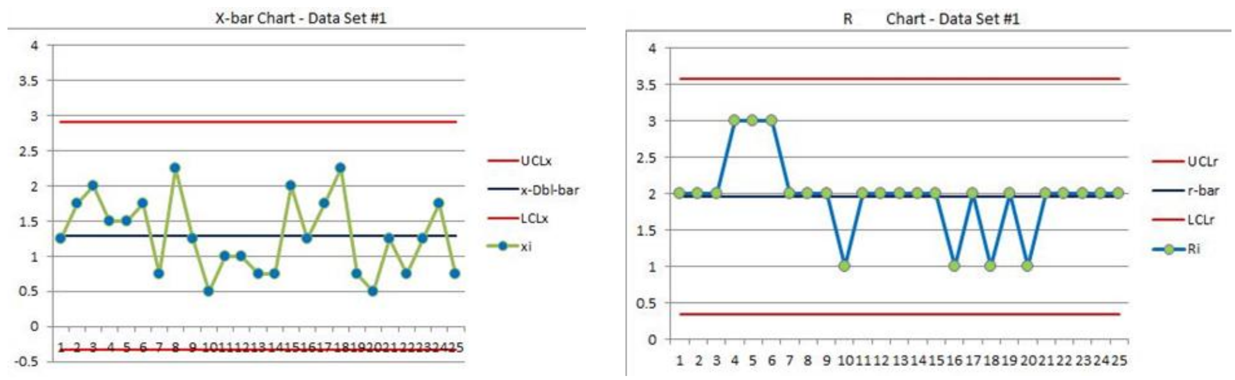
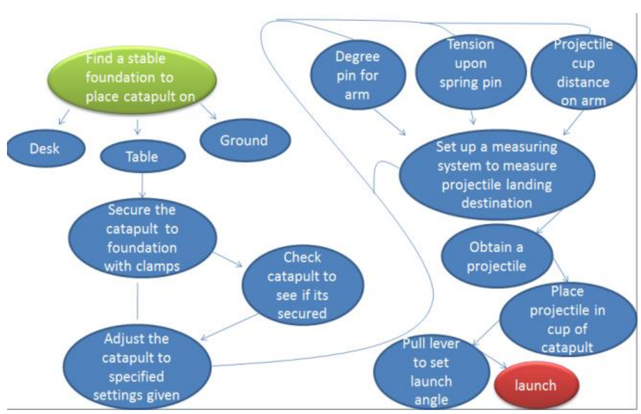


Figure 3. Initial control charts.

Next, the students began to improve the process. For each round of experiment, they used a flow chart and a cause-effect chart (as shown in Figure 4) to analyze the process and seek any possibility for process improvement. They clamped the front of the catapult to the table, increased the spring tension and moved the release point (via the stop pin). However, as they found out from the control charts, there was NO significant improvement to the process at all.



Cause	Effect
No Bushings	Pull arm off center, friction, trajectory
Rough Cup and Projectile	Uneven release, loss of momentum
No trigger system	Unable to judge correct pull back and consistent release
Clamps on two corners	Rocking motion on release, trajectory
Uneven light mount table	Rocking motion, vibration, trajectory, loss of momentum
Chalk marking system	Difficult to judge where projectile hit
No catch container	Projectile can land anywhere
Spring cyclical effect	Loss of spring force, loss of applied force

Figure 4. Flow chart and cause-effect chart to analyze the catapult firing process.

The students changed their directions to look for other opportunities for process improvement. They increased the shooting range to 18 feet and fired 100 shots. Again, no significant improvement was found.

They students continued their experiment. They replaced the flimsy roll-around table with a solid table. They also added a clamp to the rear side of the catapult. They fully expected the results to be excellent. But to their surprise, no significant change was found.

The students did not give up. They went at it again with all conditions the same but without the rear clamp. This time their results did go up dramatically with X-double bar being 2.64. About 63 of their 100 shots at 18 feet hit the little 4-inch diameter center circle of Zone 3. There were no 0's! The improved catapult setup is shown in Figure 5 and the control charts are displayed in Figure 6.

Figure 5. Improved setup of the catapult.

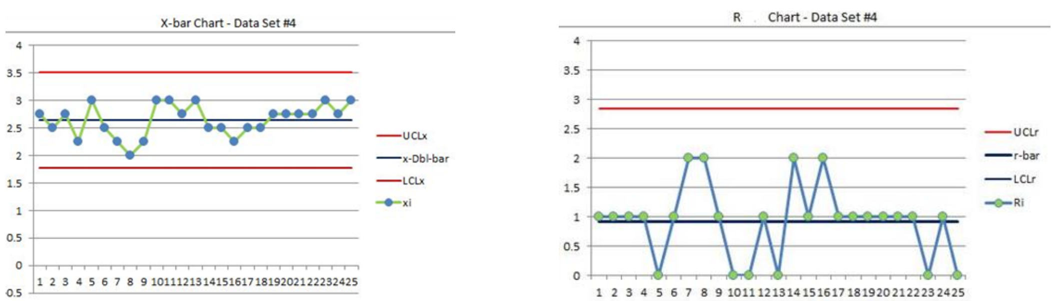


Figure 6. Control charts generated after a series of process improvement activities.

As the process improved, the students developed a standard operating procedure (as shown in Figure 7) that standardized the setup and launching process for the catapult. According to their report, by following the standardized procedure, “the accuracy and repeatability of the launching continued to be impressive”. After the process became stable, smaller target circles and farther distances were attempted by the students.

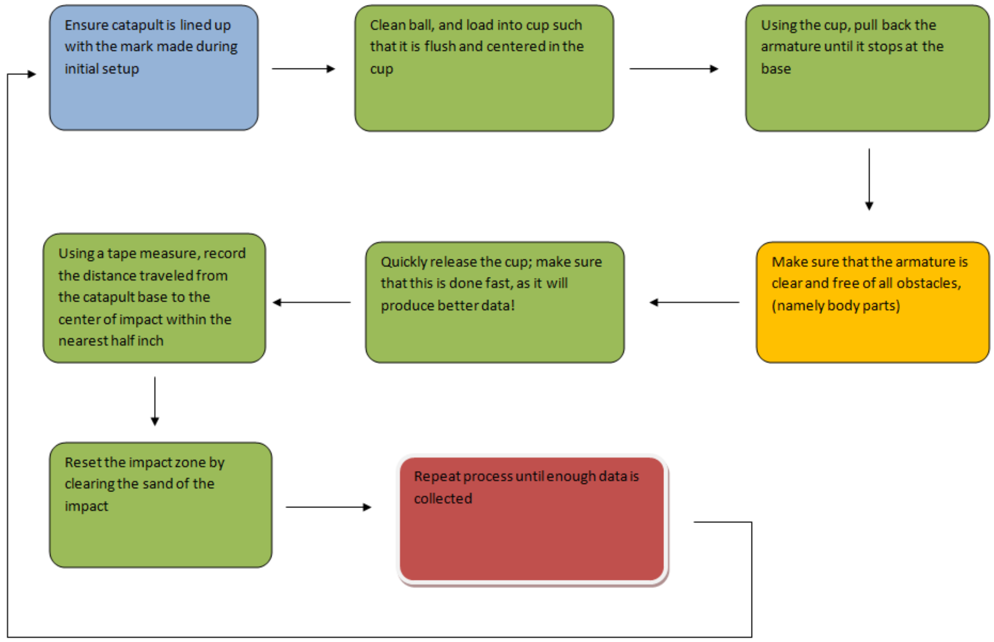


Figure 7. A standard operating procedure that standardized the shooting process.

The students drew the conclusions from the catapult project: "higher velocity-flatter trajectory approach is favored; it can be achieved by switching from a tennis ball to a golf ball, increasing spring tension, and selecting an appropriate release point with the stop-pin. If higher velocities are pursued, wear safety goggles and keep safety in mind".

The students also came up with many suggestions and ideas on how to improve the process and the catapult design. Besides the ones that have been mentioned above, other thoughts are listed below:

- Metal cans from canned food or coffee should be available and more durable than the oatmeal container. Wadded-up paper or fabric should be able to "capture" the projectile inside the can.
- Time can be saved by entering results directly into a computer rather than on paper. This saves an extra step. Make sure the computer is protected from projectiles.
- We made many changes after our first trial of 100 shots. Under ideal conditions we would limit the number of changes made after each trial to better evaluate each change. However one can well imagine the impatience of one's boss if three or four good ideas are recommended but we elect to only implement one at a time.
- If many suggestions are available for improvement, perhaps short trials of say 20 shots could be used just to help work out ideas. Regular 100 shot trials would then be used for verification.
- A digital camera can be used to record setup details, especially if other groups are sharing the equipment.

- Be consistent. If the device consistently fires high or to the left, that is fine, adjust the aim or the target. This is "cheaper" than trying to make it fire perfectly straight. If sometimes it is left and sometimes right, that is a problem worth fixing.
- We could go further to build a go/no-go type of shooting system and build a control chart for attributes. A go/no-go type of scoring would reduce the possible unreliability of eyeballing the impact point. The ball had to go in to score.
- The single side-spring could be replaced with a matching spring on either side. This would not require permanent alteration of the catapult, but might eliminate some of the off-center forces. Would it increase consistently? Only additional trials and statistical analysis would tell.
- Put a trigger on the catapult since it is tended to move when fired, and difficult to have perfect launch time after time.
- The bumper that contacted the stop pin broke. We made an emergency repair with duct tape. We suggested that this bumper needs to be improved in design to make it stronger.

The catapult experiment helped the students obtain a profound understanding about manufacturing engineering. Here are some comments they put in their reports:

- This process is useful for manufacturing because it shows how difficult it is to control a process without the use of precision data acquisition devices.
- This project shows that (in manufacturing industry) it is very easy to have high production, and low quality.
- Manufacturing is controlling processes, resources & machines.
- Decisions (in manufacturing industry) should be made based on probability distributions or calculations.
- 95% of time goes to managing waste on a worksite.
- Quality control is predicting how much quality a part will have based on measurements & charts.
- Benchmarking – finding another company that is doing a particular process better than yours, use that info to improve your process.
- Manufacturing should be controlled and boring.

The instructors used the following two rubrics (Figure 8) to formally assess the student learning outcome of MFG 333. The result was satisfactory.

Summative Assessment Rubric

Performance Criteria	Limited or No Proficiency (1)	Developing Proficiency (2)	Proficiency (3)	High Proficiency (4)	Score
1. Statistical knowledge (data collection, generation of control charts, outlier analysis, revised control charts)	Barely understand the statistical knowledge and connect it to the manufacturing process	Good statistical knowledge, but hard to connect it with the manufacturing process	Good statistical knowledge, able to set up the manufacturing with workable improvement measures	Good statistical knowledge, able to improve the manufacturing process in a systematic way	
2. Process improvement (interpretation of experiment data, all methods and justifications for stabilizing the manufacturing process)	Trial and error to make the improvements	Make improvements with some justifications	Make improvements by closely following what is found from the control charts	Make improvements by finding the in-depth causes from the control charts	
3. Evaluation of each iteration of improvement (how the experiment data get improved)	Hardly see any improvement in accuracy	Improvements in accuracy, but not stable	Improvements in accuracy, pretty stable, control limits continuously get closer after each iteration	Stable improvements in accuracy; ideas to further improvements in the future	

The students need to be reminded to relate this experiment to their manufacturing experiences. They need to give an example how a real manufacturing process can be improved by using the methodology in this experiment. They need to include this example in the lab report.

Formative Assessment Rubric

Performance Criteria	Limited or No Proficiency (1)	Developing Proficiency (2)	Proficiency (3)	High Proficiency (4)	Score
1. Statistical knowledge (data collection, generation of control charts, outlier analysis, revised control charts)	Barely understand the statistical knowledge and connect it to the catapult experiment	Good statistical knowledge, but hard to connect it with the catapult experiment	Good statistical knowledge, able to set up the catapult experiment with workable improvement measures	Good statistical knowledge, able to improve the catapult experiment in a systematic way	
2. Process improvement (interpretation of the experiment data, all methods and justifications for stabilizing the catapult setup)	Trial and error to make the improvements	Make improvements with some justifications	Make improvements by closely following what is found from the control charts	Make improvements by finding the in-depth causes from the control charts	
3. Evaluation of each iteration of improvement (how the experiment data get improved)	Hardly see any improvement in accuracy	Improvements in accuracy, but not stable	Improvements in accuracy, pretty stable, control limits continuously get closer after each iteration	Stable improvements in accuracy; ideas to further improvements in the future	

The students will do 3 rounds of experiments. Each round, they will collect the data, generate the control charts, do the analysis and improve the process. A score of this rubric will be given to each round of experiment. It is expected that the students will all get the score higher than 3.

Figure 8 Formative and summative assessment rubrics.

5. conclusions

The catapult experiment has been used in MFG 333 for 2 years. From this experiment, the students have been convinced that both the product design and the manufacturing process are the two indivisible complementary contributors to the high quality service which the product provides. The students have also become more skillful to create and analyze the control charts that can help them manipulate manufacturing processes. This experiment has helped the students better understand the basic statistical techniques which they will likely apply in their future careers.

Starting from next year, the authors will integrate the process capability (C_p and C_{pk}) analysis and control charts for attributes into the experiment to make it more comprehensive and useful for the students. In the meanwhile, the authors will collect data from the project reports and course evaluation comments to see how frequently the students use the keywords, such as "process improvement", "control chart", "control limit", "variations", "C_p and C_{pk}", and "process in control". The author will analyze if there is any correlation between these frequencies and the learning outcomes of the course.

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