Laboratory Experiments in Process Design and Optimization

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Abstract

This paper describes an approach used to teach various aspects of manufacturing process design, optimization and improvement via hands-on experiences in laboratory experimentation. The experiments were conducted using a very low cost apparatus for launching projectiles. They utilized several basic physical principles such as elasticity, gravity, sliding friction, and fluid friction. Various geometric characteristics of the apparatus and the process were used as variables. Optimization of the process for a set of goals and proof runs finished the experiments. Individual and team approaches were used for goal setting, brainstorming of expected results, possible sources of process errors and measurement errors, control of the process, preliminary test runs and what-if scenarios. These activities were included at the beginning of the experiments to teach the importance of organizational aspects of engineering experimentation and initial problem analysis.
Observations from classroom are compared to observations from an industrial setting where this experiment was used as a tool to teach concepts of Design of Experiments. The observations from both environments include some aspects of group dynamics as well as evaluation of accomplishment of objectives and setting of goals for possible further improvements. Some of the biggest advantages of this experiment are very low cost, portability, ease of reproducing in various environments and flexibility in devising objectives appropriate to analytical skill level of the students.

1. Introduction

Design of a manufacturing process, a business process or a tool to allow carrying out a given process, requires several distinct steps that entail technical as well as non-technical knowledge. The design process usually involves several iterations before the final results are achieved. The iterations involve various engineering and/or business reviews, optimization and fine tuning. These steps are clearly non-value adding activities during the design process, since they require time and tie up resources due to unforeseen difficulties, revised objectives or changed constraints.

The purely technical knowledge has been considered the core of engineering education since its very beginnings in Ecole Nationale des Ponts et Chaussées established in 1747. L'Ecole Polytechnique established in 1794, is considered to be the first engineering institution with a structured process of engineering knowledge transfer. The founders of that institution recognized

that with the ever growing body of knowledge needed for a successful career, the centuries old education model of one master and few apprentices had become largely insufficient. Education of a goal-minded individual who uses technical knowledge as a principal tool and communicates effectively with non-technical personnel became the emphasis of the education in that institution. The principles of today's engineering work have not changed much since. Increasingly more often functioning of an engineer is viewed in context of the entire scientific and economic environment. Several reports by professional societies and papers published in the last decade [1, 2, 3, 4] shed light on the growing emphasis put by the industry on development of so called 'soft skills' as a necessary component of skills possessed by successful engineers and technologists. Many examples of approaches that evaluate creativity, efficiency and overall output of engineering work are available from academic and business point of view [5, 6, 7, 8]. Newest ABET accreditation standards also require goal-oriented education that strives to define educational objectives for a program, and implement and evaluate instruments for conveying necessary knowledge. Experimentation and hands-on projects are believed to be one of the best avenues to teach the concepts of the above mentioned core knowledge and skills of present day engineers [9, 10, 11, 12, 13]. Research shows that such approach can accommodate multiple learning styles and personalities [14]. Some engineering programs have been almost totally revised to allow room for learning through doing, that is by creating educational environment that closer reflects real-world engineering practice [15].

Two Engineering Technology programs at CCSU, Manufacturing and Mechanical, require course in manufacturing process planning. The course has traditionally covered technical aspects of various manufacturing processes and technical aspects of planning a part making process (a clearly defined technical goal). Based on the author's current experience with industrial projects, several very important aspects of engineering work had to be included in the course to develop some of the skills necessary on most stages of an engineering project. The skills traditionally developed in the course were the ones based on knowledge of physics, mathematics and specifics of manufacturing processes.

The skills not emphasized in the course were the ones dealing with:

- logic
- goal setting
- establishment of metrics
- measurement of outcomes
- project reviews
- communication and documentation of project flow
- creation of various technical and business what-if scenarios
- advanced preparation for various outcomes of these scenarios
- development of feel for process variability
- establishment of 'good enough' cutoff metrics for project stoppage or continuation
- establishment of cutoff boundaries for 'too good and too costly'
- devising ways of persuasive presentation of data, participation in discussion based on evidence and achieving consensus on further actions
- working in an environment of multiple and conflicting views on project outcomes and means

of achieving the goals

The project described in this paper has a goal of developing some of the above listed skills and allowing students to experience different personalities via team work. The traditional course material has not been abandoned, but many specific aspects of some less common processes had to be left out of the course and up to individual study.

2. The Project

2.1 Goals to the project

One of the principal goals of this project is to model work environment in a setting that faces a problem with the following major characteristics:

- novel problem
- seemingly well known constraints
- adequate body of general knowledge related to the problem
- seemingly adequate body of problem-specific knowledge
- team members have experience and proven procedures of solving similar problems

Achievement of the best or optimal solution is an objective of secondary importance. This is due to time constraints of the course and complexity of the process investigated which becomes apparent only with the progress of the project.

The main goal of the project is the development of the following skills and knowledge:

- logical analysis of a problem (as a system) and its components (as inputs)
- goal setting (for the whole project and an experiment)
- ability to perform rough estimations
- feel for variability and uncertainty in final process outcome
- feel for variability and uncertainty when taking a measurement
- establishment of metrics
- measurement of outcomes
- graphical presentation of data and expected trends
- organized documentation of the following aspects of project management:
  - goals
  - plan of action (project flow)
  - project activities
  - assignment of responsibilities
  - revisions
  - accomplishments
  - conclusions and recommended future work
- logical and persuasive communication during brainstorming and project reviews
- creation of various technical and business what-if scenarios
- establishment of 'good enough' cutoff metrics

- working in an environment of multiple and conflicting views on project goals and means of achieving the goals

2.2 Introduction to the project

The project starts with no handout, no advanced preparation, and a very brief and intentionally trivial introduction. Project teams of 8 to 12 students are formed. Team size is purposely about twice the size considered to be optimal for an efficient and manageable group to simulate a common real world practice of many visionaries and few doers. The team members are also made aware of the fact that their performance will be anonymously evaluated by all members of the team at the closure of the project. Some of the 'process tools' are given to each team with no direction what to use them for and how. The 'process tools' given initially are projectiles (balls) shown in Figure 1 and projectile launching apparatus (catapult) shown in Figure 2. Intuitively, the process to be designed and optimized by the students, is a seemingly simple launching of projectiles. Other tools necessary to carry out the experiments: clamps shown in Figure 3, auxiliary tooling for drawing targets (markers and measuring tape) and vertical obstacle shown in Figure 4 are not given nor shown initially, but on demand when a group asks for them. It is done with a purpose of stimulating students' creativity in devising tools necessary for accomplishing a task.

2.3 'Process tools'

The above mentioned 'process tools' used in the project share the following characteristics:
- very low cost
- flexibility in changing existing process variables
- robustness in setting these process variables
- flexibility in devising process outputs
- portability

The whole system can be used in any classroom setting and can be easily expanded to include more process variables. For example, some part of the process variability can be studied by using a variable that physically has no effect on process outputs, e.g. color of ping-pong ball, color of golf ball, person taking measurements.

Projectiles (balls) shown in Figure 1, are from left to right:
Golf balls (differ in color only); lightweight plastic ball with dimples similar to a golf ball; ping-pong balls (differ in color only); high density foam balls (differ in size and color); soft plastic ball of a smooth surface; bouncy ball.

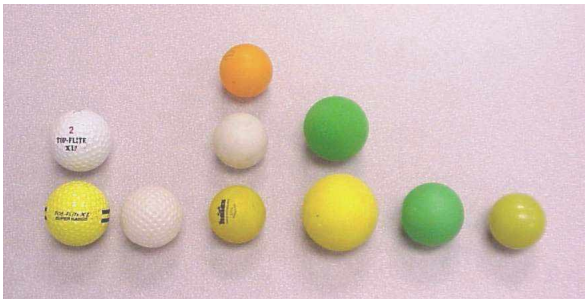


Figure 1. Projectiles used.

Projectile launcher (catapult) shown in Figure 2 has a number of possible variables, some of them can be set very repeatedly and some have an inherent variability due to the material or operation process used.

Variables of a repeatable setting:
1. Position of Arm Pin (up to 5 levels depending on Cup setting)
2. Position of Stop Pin (6 levels)
3. Position of Forward Pin (4 levels)
4. Position of ball holding Cup (up to 5 levels depending on Arm Pin setting)
5. Position of rubber band Attachment Hook (up to 5 levels depending on Forward Pin setting)

Variables of a not easily repeatable setting:
1. Arm Pullback Angle (continuous variable)
2. Rubber band length
3. Rubber band stiffness

There are also other variables that affect functioning of the catapult, but their influence seems to be smaller, hence they are not mentioned in this paper.

2.4 Project flow and instructor's role

As a rule of thumb, students start with a desire to launch the balls with no clear objectives in mind. Then the confusion quickly sets in and they ask about what the objective of this experiment is. Since the project was developed as a free-flow activity with few restrictions, the instructor's role is limited to guiding in time of confusion about what to do next, and to coaching by asking questions when an unpromising or unrealistic path is undertaken.

Once a team realizes that they must have an objective of their actions, the following 3 goals are mentioned most often:
- How to achieve the longest travel distance
- How to precisely hit a target (bulls eye in vertical plane)
- How to destroy a target

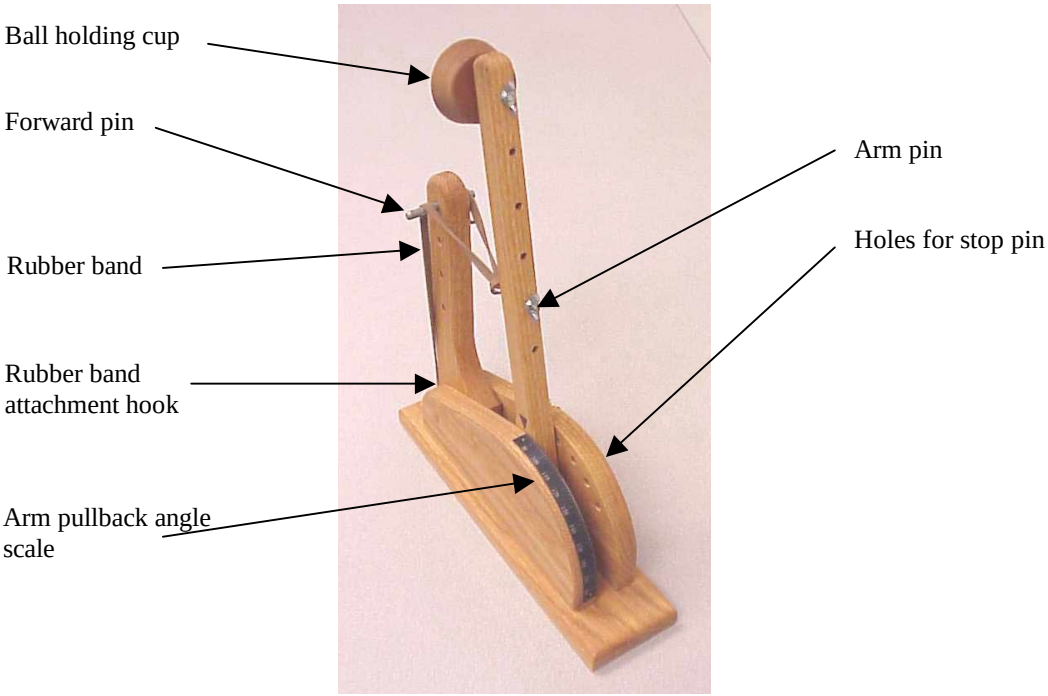


Figure 2. Catapult.

Figure 3. Clamps for holding the catapult.

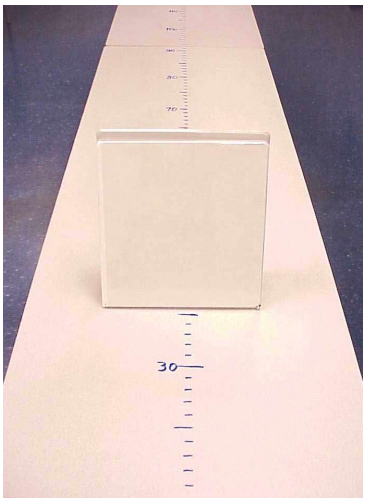


Figure 4. Vertical obstacle.

The experience with the project shows that students always have to be guided to slow down their desire to start the experimentation, and to document the following thoughts and decisions about:

- Process objectives (project objectives)
- Process variables
- Process constants
- Process constraints
- Estimated influence of each previously listed variable
- Estimated ease of setting each listed variable
- Estimated variability of each listed variable
- Variables to be used in the experiments
- Levels of each variable to be set as a constant
- List of environmental variables and their settings (if replication is needed)
- Estimated run time

Good documentation of project activities and decisions related to the investigated process is one of the most important things required from the project team. A team is not allowed to proceed with experiments until a good documentation of the above listed goals and decisions is made. As a rule, only at the end of the project, the students realize that these seemingly bureaucratic activities are real time savers. I view this as one of the important skill-building outcomes of the project. The documentation is a part of project deliverables.

Experimentation begins with proofing runs to verify the setup and procedures. Any necessary changes are then implemented and the experiments can begin.

Due to time constraints of the course and very limited students' knowledge of statistical software, the instructor does the statistical analysis of experimental data. The team is required to submit experimental data electronically in a set format. Analysis results are then given to the team for interpretation and decisions on further actions.

All decisions and future recommendations that due to time constraints cannot be implemented in class are submitted in writing with specifications about the following:

1. <u>What</u> to do
2. <u>How</u> to do it
3. What is <u>expected</u> as a <u>result</u>
4. Done <u>by who</u>
5. Done <u>by when</u> (duration)

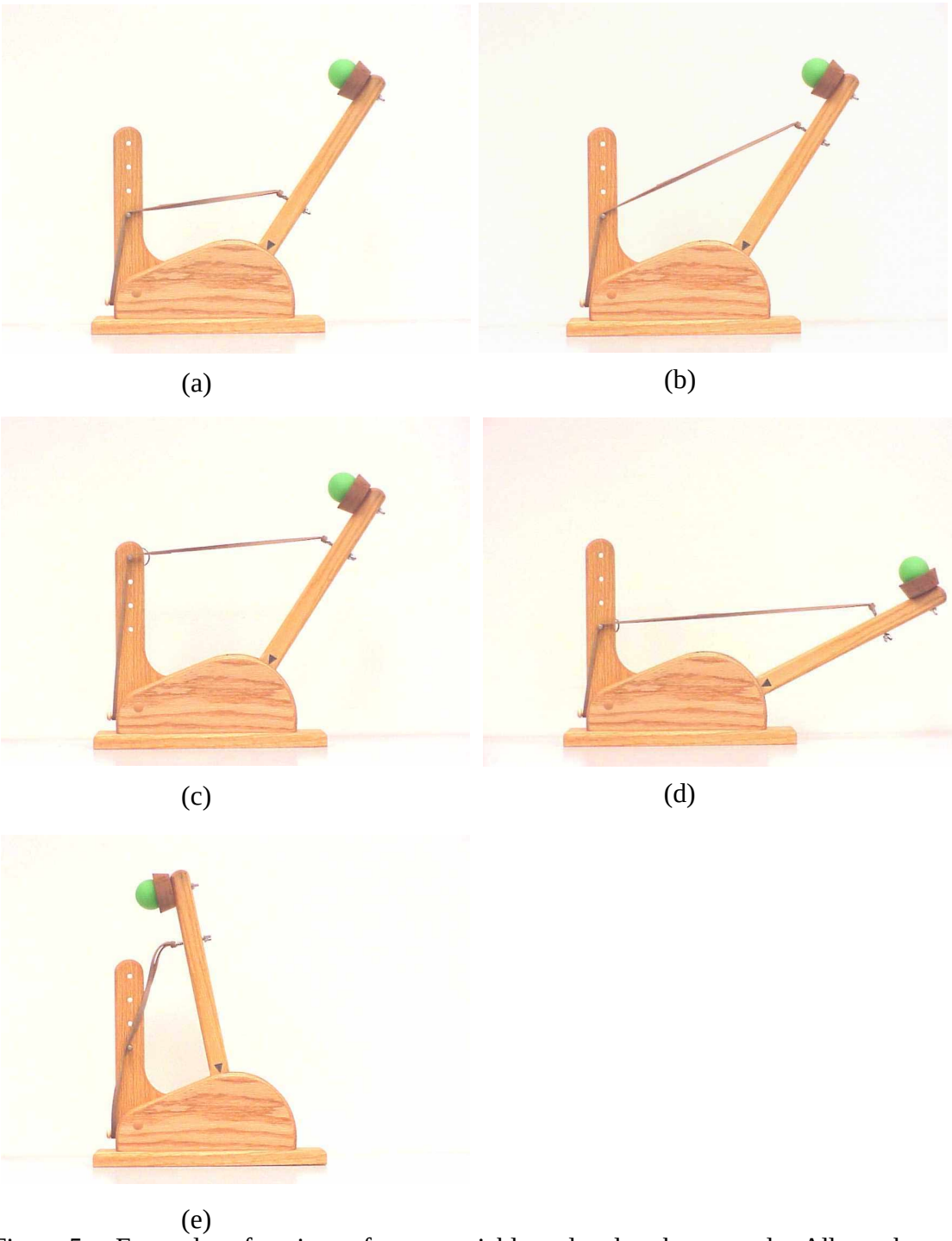


Figure 5. Examples of settings of some variables related to the catapult. All are shown at the position of ball being ejected from the cup. Arm Pin and Forward Pin (a, b, and c). Stop Pin (b, d and e).

2.5 Experimental setup

The physical setup of the whole experiment is also left up to the team. The 3 goals of the process which are most often chosen by students (listed in section 2.4) can be accomplished at virtually no cost, just like the rest of this experimental project. An example of setup is shown in Figure 6 and its variant in Figure 4.

The setup demonstrated in Figure 6 shows clamping of the catapult to the table. When students inquire about clamping the catapult, they are given the two spring clamps (Figure 3). Initially they are satisfied with them, but during the obligatory initial runs, they sometimes discover that the back clamp is not stiff enough and allows the base to move when arm hits the stop pin. If this finding is made, a much stiffer clamp (carpenter's clamp shown in Figure 3) is given. The original and improved clamping are shown in Figure 7.

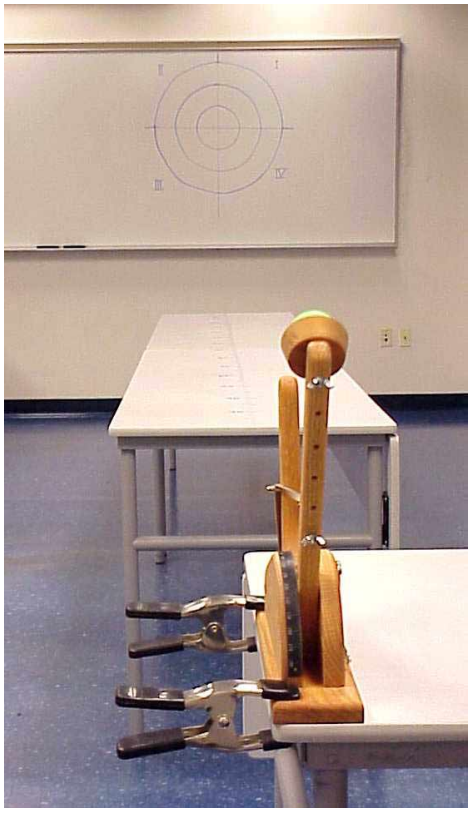
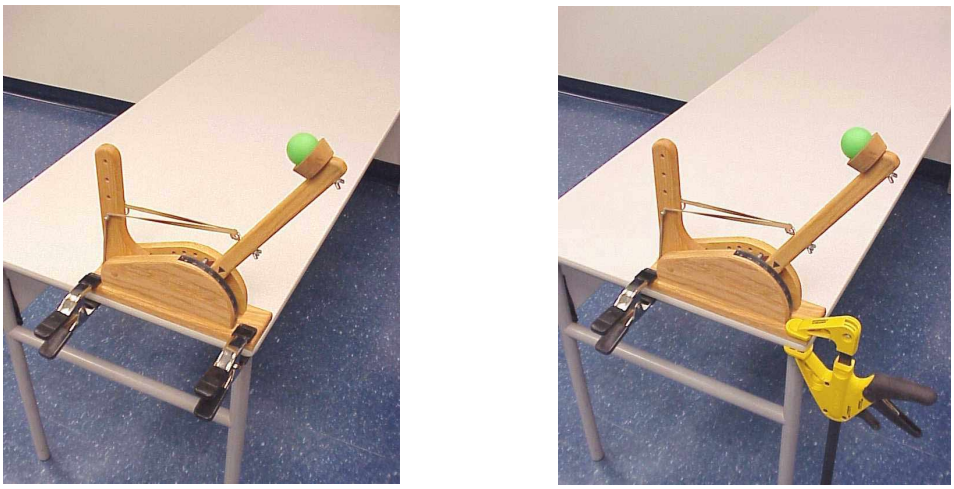


Figure 6. Example of an experimental setup showing two process objectives: shooting at a vertical target (bulls eye on the white board) and launching for distance (scale drawn on the tables).



(a) (b)

Figure 7. Example of clamping using spring clamp (a) and carpenter's clamp(b).

3. Experimental investigation of the process

3.1 Process goal

This section describes an example of experiment and its results. One team has chosen the greatest horizontal distance of projectile flight as a goal of the process. To achieve the process goal, the process output (R1), the horizontal distance of projectile flight, was measured. The process was investigated through Full Factorial experimentation, in order to avoid introduction of Fractional Factorial designs, which would require too much time to explain. After results of the Full Factorial experiment were ready, the same experimental data was used to illustrate the would-be results if Fractional Factorial designs were used for the experiment. That was done by taking into consideration only results from runs having variable settings pertaining to the Fractional Factorial design used.

3.2 Process variables, constants and noise

Through brainstorming, the project team generated a list of 29 variables of the process. Assuming only 2 levels of each variable, the Full Factorial experiment would require 2^{29} runs. Assuming non-randomized experiment and only 1 minute between projectile launches (includes time for setting each variable, launching the ball and measuring the distance) the experiment would take almost 1021 years. The number of variables was than quickly trimmed. Some variables were grouped and included in another variable (e.g. physical properties of balls were grouped into a new variable called 'Ball Type'. The remaining variables were set as constants or not controlled (treated as random noise or environmental noise). The final number of selected variables was 5. These variables are listed in Table 1, along with the number of available settings and the number of settings chosen for the experiment.

The sixth variable, F, (Distance Measurer) was added to investigate influence of a human on

distance reading accuracy.

Table 1. Process inputs and output.

Variable name	Variable symbol	Variable type	Unit	Number of available settings	Number of settings used	Low level (- or 1)	High level (+ or 2)
Arm Pin position	A	Discrete	--	5	2	1 (bottom)	3
Stop Pin position	B	Discrete	--	6	2	2 (=142°)	3 (=126°)
Forward Pin position	C	Discrete	--	4	2	2	4 (highest)
Ball Type	D	Discrete	--	6	2	Green foam	Bouncy
Arm Pullback Angle	E	Continuous	deg	∞ (e.g. 4)	2	160°	188°
Distance Measurer	F	Discrete	--	e.g. 2	2	P	J
Response name	Response symbol	Response type	Unit				
Horizontal Distance	R1	Continuous	inch				

Assuming 30 seconds between launches, estimation of experiment run time gives the following:

- when using all available settings: 5x6x4x6x4x2 = 5760 runs, 48 hours
- when using only 2 setting for each variable: 2^6 = 64 runs, 0.5 hour

Since for each launch 2 readings were taken simultaneously, one by each distance measurer (variable F), the total number of launches executed was 32, giving the estimated run time of 0.25 hour.

3.3 Experimental results and analysis

Figure 8 shows one of the plots to be analyzed by the team members. The below Minitab printout of General Linear Model procedure shows the significance level of each variable. The plot shows that on the average, the second distance measurer (J) reads longer distances than the first one (P). The printout shows also, that the significance of the distance measurer is extremely low (using obviously one of the two measurers), and that all other variables are significant to the process output. Therefore, either one of the two distance measurers can be used. Both, the figure and the printout illustrate that the most influential variable is Arm Pullback Angle (E), followed by Forward Pin Position (C) and Arm Pin Position (A). In order to achieve the longest ball launch distance, all the process variables should be set at their high settings.

For a desired specific length of ball flight the below shown linear regression equation was used. A 150 inches ball flight can be achieved by using for example: Arm Pin at 3rd hole, Stop Pin at 2nd hole, Forward Pin at 4th hole, green foam ball, 188° Pullback Angle, and any of the two measurers. Confirmation tests were run to verify correctness of the predictions. The regression equation has adjusted coefficient of determination of about 87%. Using the results of regression analysis, students have noticed that using some variables as quantitative with more physical meaning (e.g. arm angle at launch point instead of hole number) can give a better understanding of the process, and facilitate process optimization. Additional analysis was also performed, but is not included in this paper.

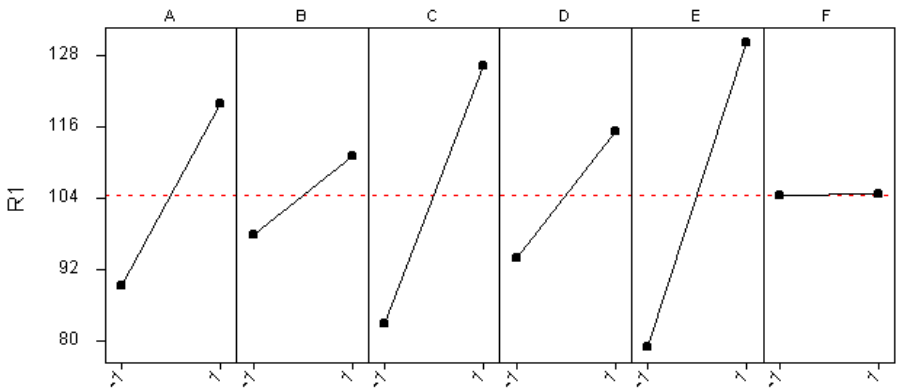


Figure 8. Main effects plot for data means for response R1 (horizontal distance of projectile travel).

General Linear Model

Factor	Type	Levels	Values
A	fixed	2	-1 1
B	fixed	2	-1 1
C	fixed	2	-1 1
D	fixed	2	-1 1
E	fixed	2	-1 1
F	fixed	2	-1 1

Analysis of Variance for R1, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	1	14945	14945	14945	63.51	0.000
B	1	2809	2809	2809	11.94	0.001
C	1	30102	30102	30102	127.93	0.000
D	1	7268	7268	7268	30.89	0.000
E	1	41923	41923	41923	178.16	0.000
F	1	1	1	1	0.00	0.948
Error	57	13413	13413	235		
Total	63	110460				

Regression Analysis

The regression equation is

R1 = 105 + 15.3 A + 6.62 B + 21.7 C + 10.7 D + 25.6 E

R-Sq = 87.9% R-Sq(adj) = 86.8%

4. Conclusions

Some of the biggest advantages of this experiment are: very low cost, portability, ease of reproducing in various environments and flexibility in devising objectives appropriate to available time and analytical skill level of the students. This project was by far less expensive then the previously used project that involved joining of metal pieces and destructive testing. It also achieved much better educational results in the matter of process design, improvement and optimization. That was mainly due to less time spent on learning the system and its physical principles, and more time spent on doing the project. The project allowed the team members to devise their own process and project goals, self-evaluate their work and results, and create activities leading towards further improvements. As compared to the previously used project, instructor's preparation for the described here project was much faster and logistics of its running much simpler (not much can go wrong with the catapult).

My observation from running this project in academic and industrial settings, indicates that students like playing with the apparatus, treating the whole process like a sports competition (*Citius, Altius, Fortius*). That is probably due to the fact that the physical process used in the project has elements of faster, farther, stronger and more precise; all very easy to visualize and measure. Setting process goals and deciding on process inputs, constants and measurable outputs was somewhat easier with industrial participants. They were more to the point, and more responsible for their part of work. Both types of students, academic and industrial, were equally reluctant to document, and needed guidance in self-organization. The 5 point requirement for future developments (listed in section 2.4) has proven to be a better tool for reporting that part of concluding remarks than conclusions written in a traditional way.

Group dynamics always showed occasional 'slackers' in the academic course but no such behavior in the industry. On the other hand, there were no grumpy team members among university students, whereas in the industry, there was sometimes one individual who 'knew all that was to be known'. Team leaders in academic setting led by initiative and carrying more workload. Team leaders in the industry led by suggesting, ney-saying, overseeing and ordering. That behavior reflected daily work relations and reporting among team members.

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