Using Design of Experiments and the PDSA to improve 3-D Printing in a Senior-Level Quality Course

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Abstract

Research has shown that project-based learning (PBL) is more engaging than traditional teaching methods. A proposed PBL method using two cycles of plan-do-study-act (PDSA) coupled with design of experiments will be tested as means for delivering PBL effectively. A senior-level project will demonstrate how PDSA and design of experiment can be used together to both learn about a manufacturing process and how to improve it.

Students will be using three existing laboratories with manufacturing processes to demonstrate the proposed method with the 3-D printing as the featured project. As additive manufacturing in the form of 3-D printing is becoming more popular in research and in limited production runs, it still has many challenges when it comes to manufacturing at a large scale. These challenges include cost of making the product as well as speed of production. While these challenges are technology-based, studying current 3-D printing processes for improving quality and reducing cost can still be conducted. Students are asked to study the process and identify factors that impact quality and productivity with the objective of improving both.

The aim of this study is to determine the impact of the proposed PBL method on process improvement and learning. The paper will attempt to answer the following questions: (1) Can the manufacturing process be improved using the proposed method in existing labs? and (2) Will students learn better using at least two iterations with PDSA and design of experiments?

Introduction

Research shows that students learn better if they are engaged in, and motivated to struggle with, their own learning. For this reason, if no other, students appear to learn better if they work cooperatively in small groups to solve problems [1]. Collaborative learning has been described in college level courses in various forms [2], [3], [4], [5], [6]. Educators employing collaborative or cooperative learning methods reported greater student satisfaction with the learning experience [4], [5], reduction of anxiety [7], and concluding that student performance was greater than individual students could have achieved working independently [2], [6].

In a comprehensive metaanalysis of 225 studies comparing student performance in undergraduate science, technology, engineering, and mathematics (STEM) courses when using traditional (lecturing) methods vs. active learning, the results were overwhelmingly in favor of active learning [8]. For example, the results of this metaanalysis show that, on average, the failure rates for students under traditional lecturing increase by 55% over those observed in courses with active learning. The problem is underscored by the observation that less than 40%

of US students (and 20% of underrepresented minority students) entering the university with an interest in STEM finish with a STEM degree [9].

In contrast with traditional engineering education, which is taught deductively starting with theories and progressing to application, a preferable approach is inductive teaching and learning [10]. Inductive teaching and learning encompass many instructional methods such as problem-based learning, case-based teaching, and project-based learning, among others. Using such methods, one could start with a set of observations or experimental data where problem statement or goals are determined. Based on the analysis of such data, students would generate the need for additional data and/or procedures to help them learn themselves.

In their analysis of several inductive learning methods, Prince and Felder identified features for project-based methods as compared to other active-learning methods such as guided inquiry, problem-based, case-based, discovery, and just-in-time teaching [10]. Project-based learning is usually collaborative (team-based) that essentially requires a major project to provide the context for learning. The project is made up of tasks that lead to an outcome which could eventually be a procedure or a model to produce a desired product or service consistently.

Another key feature of a project-based learning (PBL)is that assigned problems are more open-ended than, say, problem-based learning, which means that the outcome is unknown to both instructor (facilitator) as well as students. In a PBL environment, a team of students would begin by formulating a plan or strategies for tackling an issue by dividing it into logical tasks with assigned responsibilities and due dates. The project may have several objectives based on the problem statement. Therefore, adjustments based on studying intermediate results are typically made along the way. Applying knowledge gained during implementation is a typical feature of PBL in progressing towards the end product or goals [10]. The aim of this research is to provide learning opportunities for students that will enable them to transfer the knowledge gained into real work settings. Based on their comprehensive survey, Bransford et al. provide strong support for inductive learning methods [11]. Among their findings is that the new learning involves knowledge learned previously.

Improvement Methodology

Deming introduced to the world the notion of seeing systems in what he coined as a System of Profound Knowledge (SoPK). It is comprised of four parts that must work together: appreciation of a system, variation, theory of knowledge, and psychology [12]. These parts have been linked to much research work that has been done since then. This includes, but not limited to, transformational leadership [13], organizational transformation [14], learning organizations [15], [16], motivation [17]. In his book, *The New Economics*, Deming sees theory of knowledge as way that "helps us understand that management in any form is prediction" [12, p. 69]. According to Deming, "Rational prediction requires theory and builds knowledge through systematic revision and extension of theory based on comparison of prediction with observation." For example, demonstrating a competency in an engineering lab requires instructions or a procedure.

Based on the procedure at hand, we predict a certain outcome when procedural steps are performed as prescribed. The outcome of the demonstration (observation) is compared to prediction (expectation). A noticeable difference between observation and expectation may require revision of the procedure (theory) then applying it again in order to gain knowledge.

A robust methodology for acquiring knowledge is the Deming Cycle of Plan-Do-Study-Act or PDSA. Deming refers to it as the Shewhart Cycle [18]. Figure 1 shows that the PDSA cycle is continuous and thus guarantees the temporal dimension for the theory of knowledge. In other words, knowledge is gained after each cycle and future cycles are undertaken with accumulated knowledge.

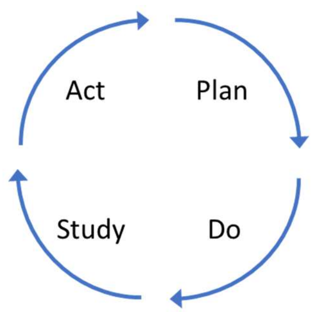

Figure 1: Plan-Do-Study-Act (PDSA) Cycle

Table 1 shows the phases of the PDSA cycle along with what each phase involves. Deming described it as a flow diagram of learning and improvement to the product or service [18].

Table 1: PDSA Details

Phase	Description
Plan (P)	Plan a change or test aimed at improvement by stating objective, questions, and predictions
Do (D)	Carry out the change or run the experiment and document problems and issues
Study (S)	Analyze data graphically and statistically. Use earlier analysis to build a temporal picture. Compare to prediction (expectations)
Act (A)	What was learned and what changes are needed? Are there issues with the learning process? If another PDSA cycle is needed, go back to Plan (P)

Project Details

Feedback received from a previous research study, where a process simulator was used, indicated that students were interested in real processes to work on and improve [19]. For time constraints and lack of manufacturing companies close to campus, opportunities for projects were identified in laboratories utilized for teaching plastics technology as well as additive manufacturing using a 3-D Printer. These projects were a part of a new senior engineering course on quality process analysis and was offered as a technical elective in an engineering technology and management program. The course included both traditional components (classroom lectures, homework, and in-class work), as well as the project component. Below is information related to the scope of the project:

1. Each of the assigned projects was open-ended with no known solution
2. Engineering laboratories were utilized for making actual products. The three processes involved were:
    a. Thermoforming (plastics)
    b. Rotational molding (plastics)
    c. Additive manufacturing (3-D printing - plastics)

    It should be noted here that students engaged in a lab competency for any of the mentioned processes at the sophomore-level follow an established procedure (setup sheet), observe the outcome, label the item and prepare a report based on their observations. The outcome is typically known and rarely deviates from expectations. In this deductive-style of learning, students rely on someone else's experience to set up the process parameters for them.

3. Each project starts with a "theory" and would not be based on anyone's experience. The current setup sheets for the assigned lab competencies were considered the "theory" or starting point.
4. The common objective for the three projects is to improve current processes for demonstrating lab competencies by:
    a. Minimizing defects
    b. Reducing cycle time
    c. Reducing energy consumption or material use, as applicable

    These objectives are aligned with real-world manufacturing processes where the aim is to economically produce products that the customer wants.

5. Problem solving techniques such as design of experiments and other applicable methods to minimize variation and improve performance were used.
6. A statistical software will be used to analyze the data

As PBL methods are different from one another, this research can be differentiated by following PDSA process with a minimum of two cycles to demonstrate its effectiveness for improvement. In addition, design and analysis of experiments were utilized for both understanding the process as well as improvement. The aim of this paper is to show how the PDSA cycle and design of experiments can be used together to understand and improve manufacturing processes. The process featured in this paper is the 3D-printing, also known as additive manufacturing, and was selected for its current popularity and future potential. It is only used as an example of demonstrating the proposed PBL method.

3-D Printing or additive manufacturing (AM) started in the early 1980's in rapid prototyping then progressed to tooling [20]. Over time, several AM technologies emerged to process different types of materials including polymers, ceramics, metals and composites [21]. While still limited in high production capabilities, AM technologies are making big strides in manufacturing for their reduction of waste, elimination of the use of tooling for making objects, and quicker response to market [21]. For this, future engineers should have better understanding of how to reduce cycle time while still meeting functional and quality characteristics of the product being made.

The team utilized a 3-D printer in one of the engineering labs using polymer and based on fused deposition modeling technology. The 3-D printer melts PLA filament and squeezes it out onto the build platform in thin lines to build the object. Time to build the object depends on the settings of other factors discussed in the next section.

Initial PDSA Cycle

The PDSA is detailed for the 3-D printing project in Table 2. The team identified all the steps and deliverables for each phase.

Table 2: PDSA for 3-D Printing Project Using Designed Experiments

Phase	Description
Plan	• Define process (parameters and responses) • State problem / voice of the customer • Determine objectives • Design experiment / data collection sheets • Verify measurement system • Verify 3-D printer and inputs • Schedule experiment
Do	• Carry out experiment • Measure responses and Record data
Study	• Analyze experiment using mean and interaction plots • Which factors are statistically significant? • Study impact of factors involved • Determine best settings
Act	• Conclusions from the PDSA phases • What is the prediction model? • Which factors can be fixed at economical settings? • Which factors need to be investigated further?

Using Table 2, the team kicked off the project to be completed within a semester. A report and presentation were expected with a minimum of two PDSA Cycles.

Plan:

- **Process Definition**: 3D printing is the process of making a solid product bases on a digital model (e.g. 3D CAD model). In this process, the printer adds thin layers – one by one – until the model is built. The team built a basic product which includes round and straight surface with expected weight of 5 to 10 grams. Figure 2 shows a sketch of the designed object. The team determined the following as responses to measure the following:
  1. *Surface defects* where the objective is to have zero defects
  2. *Height dimension* where the specifications are 1.000±0.015 inches
  3. *Cycle time* of production (printing) in minutes
  4. *Weight* in grams

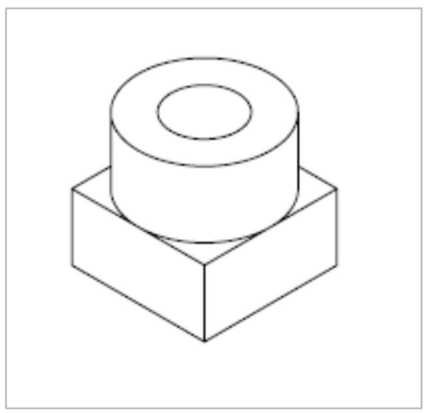

Figure 2: Sketch of Printed Object

The aim is to print a defect-free desirable parts with the least amount of waste. The team identified several controllable process parameters to be investigated:

1. *Layer height*: the thickness of each layer which eventually determines the surface finish where lower heights result in smoother surface
2. *Infill pattern*: The pattern used to fill the interior of the object
3. *Infill percentage*: The density of material that comprises the interior of the object housed between the shells.
4. *Nozzle temperature*: Temperature of the end where molten material is extruded
5. *Number of shells*: this refers to the number of times maximum thickness of the outer wall when compared to the nozzle's diameter.
6. *Travel speed*: The speed in mm/sec. that the printing head moves.

- **Statement of the problem / voice of the customer**: Current 3D prints have been showing some surface quality issues for the different product generated with varying cycle time and wasted materials. The customer receiving the 3D prints wants product with no surface issues. The product should also be strong, and consistently within tolerance – as close to nominal as possible.
- **Project objectives**: Using at least two cycles of PDSA and design of the experiments, the aim of this project is to identify the process factors that affect quality and to what extent. It will also attempt to locate the best settings for these factors so that high quality products are produced.
- **Designed Experiments**: Using available statistical software, the team designed a fractional factorial experiment at two levels to minimize the number of runs. Table 3 shows the factors and their levels which were decided based on prior knowledge and the feasibility of producing parts.

Table 3: Factors and their Settings

Factor	Level 1	Level 2
Layer Height	0.15 mm	0.25 mm
Infill Percentage	10%	18%
Nozzle Temperature	210 ºC	220 ºC
Number of Shells	1	3
Travel Speed	125 mm/s	175 mm/s
Infill Pattern	Hex	Grid

The experimental design in Table 4 uses the technology of (-1) and (1) to indicate level 1 and level 2, respectively. This is based on a 2^{6-3} fractional factorial design (one-eighth fraction of the full factorial) with a total of 8 runs.

Table 4: Fractional Factorial Design

Run	Nozzle Temp	Number of Shells	Infill Pattern	Travel Speed	Layer Height	Infill %
1	-1	-1	-1	1	1	1
2	1	-1	-1	-1	-1	1
3	-1	1	-1	-1	1	-1
4	1	1	-1	1	-1	-1
5	-1	-1	1	1	-1	-1
6	1	-1	1	-1	1	-1
7	-1	1	1	-1	-1	1
8	1	1	1	1	1	1

While quality defects were evaluated visually through consensus by team members, the height and weight were measured using validated calipers and scale, respectively. The cycle time is given by the 3D printer report.

The 3D printer was verified and was in good working conditions. Time commitments by team members were coordinated to cover the scheduled runs. There was also enough PLA Filament (polymer) to cover printing needs.

Do

The experimental runs were conducted in a random order since changing between settings for any factor was not time consuming. Table 5 shows the experimental data as collected.

Table 5: Experimental Data for Initial PDSA

Run	Nozzle Temp	Shells	Infill Pattern	Travel Speed	Layer Height	Infill %	Time (min)	Height (in)	Defects	Weight (gm)
1	210	1	Hex	175	0.25	18	29.5	1.019	2	5.4
2	220	1	Hex	125	0.15	18	45.75	1.006	4	5.2
3	210	3	Hex	125	0.25	10	29.5	1.014	3	6.6
4	220	3	Hex	175	0.15	10	42.25	1.009	2	5.9
5	210	1	Grid	175	0.15	10	38.25	1.007	4	4
6	220	1	Grid	125	0.25	10	28.5	1.013	3	5.6
7	210	3	Grid	125	0.15	18	45.5	1.007	3	7.1
8	220	3	Grid	175	0.25	18	32.25	1.009	3	7.9

Study

Utilizing a statistical software, analysis of variance (ANOVA) as well as means plots were generated. Table 6 shows which factors are significant (level of significance). Surface defects and height were not significantly impacted by any of these factors.

Table 6: Significant Factors for Initial PDSA

Factor	Time	Weight
Nozzle Temp		
Number of Shells		Sig (.026)
Infill Pattern		
Travel Speed		
Layer Height	Sig (0.000)	Sig (0.058)
Infill %		Sig (0.054)

Act

From results in Table 6, Layer height and number of shells will be investigated in the second PDSA while other factors may be set at their best economical levels. It should be noted that interaction effects among factors were not considered in the model since the main objective here is to screen the factors and identify which ones to analyze further.

The team observed that some of the defects found were related to the printer head (nozzle tip) for not being clean and not necessarily a defect related to changes in levels for the factors. This could be a reason why, although reported as defects, they were not influenced by any of the process factors. This will be reported as a step in the 3-D printing process setup.

Second PDSA Cycle

<u>Plan</u>

Based on the findings of the initial PDSA, a second PDSA was set up and carried out. In this cycle only two factors were considered as shown in Table 7. Since higher values of *Layer Height* produced better results, it seemed appropriate to explore more in that direction. Similarly, the number of shells produced better results over all responses when the number of shells increased. For the second PDSA, a new level of "5" will be used in addition to "3" for *Number of Shells*.

Table 7: Factors and Their Settings - Second PDSA

Factor	Level 1	Level 2	Level 3
Layer Height	0.20 mm	0.30 mm	0.40 mm
Number of Shells	3	5	

All other factors in the initial PDSA were held constant at their most economical settings as follows:

- Nozzle Temperature = 210 ºC
- Infill Pattern = HEX
- Travel Speed = 175 mm/s
- Infill % = 10%

A general factorial design was used for this experiment with 6 combination (3 levels for *Layer Height* x 2 levels for *Number of Shells*). The design is shown in Table 8

Table 8: General Factorial Design - Second PDSA

Run	Shells	Layer Height
1	3	0.2
2	3	0.3
3	3	0.4
4	5	0.2
5	5	0.3
6	5	0.4

Do

The experiment was conducted as in the initial PDSA. There were 6 experimental combinations to run and results are shown in Table 9.

Study

Using the statistical software, data was analyzed using analysis of variance (ANOVA) as well as means plots. Table 10 and Figure 3 shows the impact of the two factors on all responses.

Table 9: Experimental Data for Second PDSA

Run	Shells	Layer Height	Time (min)	Height (in)	Weight (gm)	Defects
1	3	0.2	34.7	1.011	6.2	2
2	3	0.3	25.6	1.013	6.5	2
3	3	0.4	20.2	1.003	6.6	2
4	5	0.2	41.6	1.012	8.1	3
5	5	0.3	30.4	1.012	8.6	4
6	5	0.4	23.9	1.003	8.8	5

Table 10: Significant Effects from Analysis of Variance

Factor	Time (min)	Height (in)	Weight (gm)	Defects
Number of Shells	Sig (0.032)		Sig (0.002)	Sig (0.074)
Layer Height	Sig (0.010)	Sig (0.009)	Sig (0.067)	

Based on the above results, the following settings (Table 11) from both PDSAs can be used to improve the process significantly. Namely, the new settings would keep weight at a reasonable value to minimize:

1. Material use / waste
2. Cycle time
3. Deviation from target height value
4. Surface defects

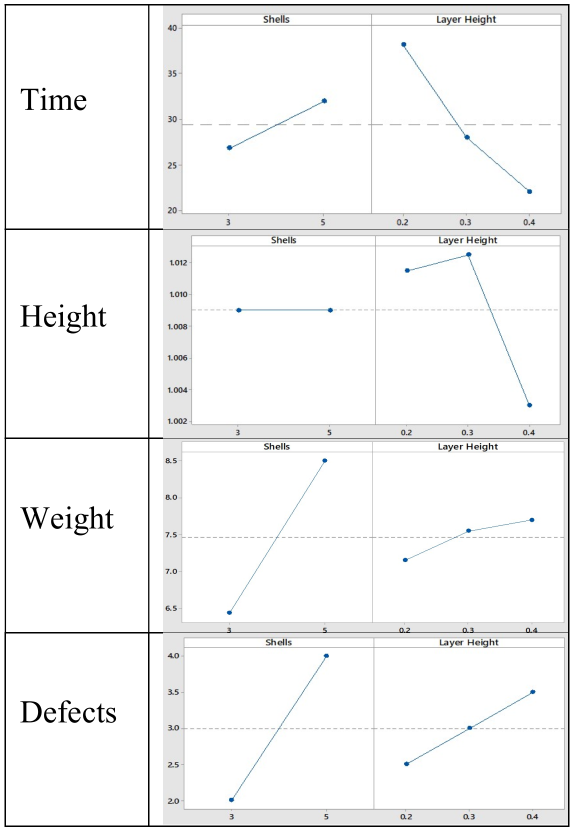

Figure 3: Means Plots for Second PDSA

The first four settings (i.e. settings for *Nozzle Temperature, Infill Pattern, Travel Speed,* and *Infill%*) were decided from the initial PDSA and the last two, *Layer Height* and *Number of Shells*, were decided based on accumulated knowledge from both PDSA Cycles.

Table 11: 3D Process Best Settings

Factor	Best Setting
Nozzle Temperature	210 ºC
Infill Pattern	HEX
Travel Speed	175 mm/s
Infill %	10%
Layer Height	0.4
Number of Shells	3

<u>Act</u>

For this phase, a regression model for prediction can be generated for each response. Once a response is predicted, it can be validated against an actual run (product made from the best settings). If prediction is reasonably close with a tight 95% prediction confidence interval, the process would be accepted with no further PDSAs to carry out. Otherwise, further investigation is needed with additional PDSAs.

The team was asked to evaluate the learning process using the PDSA by answering a few questions. In addition to the 3-D project team, the other two teams provided their feedback as well. There were four questions for feedback. The first question was related to the importance of documenting the current process in the "Plan" phase and why. The responses were similar in indicating that it is very important because it is needed as a reference for any improvement. The second and third questions are summarized in Table 12. The fourth question asked for any additional feedback which is summarized in the "Concluding Remarks" section

Table 12: Student Feedback (10 Students)

If you had not used design of experiments, what would you have used instead to understand your process? 8 out of 10 students indicated that they would use trial and error or experimenting one-factor at a time. Two students would either flowchart the process or not sure what to use.
What lessons have been learned from using the plan-do-study-act cycle (PDSA) and design of experiments (DoE)? Students had the following (or similar) comments: • "I have learned more in understanding how to find factors within a process and tweak those factors so that they can help eliminate variations within a process. Which in return will help standardize a process" • "Basically, just the correct way to conduct a test study and the proper way to find the root causes within a process" • "I have learned how to improve processes and control factors by using these improvement methods. I've learned that every step in the process is necessary to improve processes" • "I have learned that the PDSA never ends..." • "It is an organized and fairly simple way to come up with the best outcome"

Concluding Remarks

In this project-based learning study using existing labs, students were far more engaged in the process than during traditional segments of the course. Utilizing the PDSA cycle gave them a platform to carry out their projects successfully. One of the objectives of this study was to show how knowledge from the initial PDSA cycle can be used in the next cycle.

The first question of this research was related to the results of the improvement to the manufacturing process. In other words, did the process improve? As indicated in the analysis of the designed experiments of the 3-D project, improvements were made in the cycle time and quality of the printed parts. Such improvements will be incorporated in the standard being used in printing producing parts using the 3-D printer. Similar improvements were also made in the other two projects; the rotational molding and thermoforming processes. Such improvements will be used in process set up and demonstrations in classes where these technologies are being used.

The second question of this research was related to the methodology used (two cycles of PDSA and design of experiments). Typically, continuous improvement projects using methods such as Six Sigma's DMAIC process are completed in one cycle. In this research, each team had to go through a minimum of two cycles to emphasize the sequential nature process improvement. That is, accumulated knowledge from one cycle is used to make further improvements in the next cycle, and so on. When confronted with many process factors affecting the quality and cycle time, the first PDSA cycle would include a screening experiment to identify the important factors. The next cycle may be used for experimenting with those factors that were deemed significant in order to optimize quality and minimize waste. The 3-D project summarized in this paper demonstrated how the knowledge gained from the initial PDSA cycle is used to determine the factors and levels used in the second cycle. Table 12 summarizes how students perceived the proposed methodology in manufacturing process improvement.

When asked for additional feedback on this experience, students thought that it was a good experience. One student noted "Conducting more lab experiments and actually measuring products that were made instead of just random data helped understand the concepts..."

As indicated above, process setups generated from these projects will be shared with the appropriate labs to implement as validated process setups for producing best results (i.e., producing better quality with less waste).

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