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CASE STUDY

Improving 3D printing laboratory operations: a case study of lean six sigma implementation

Octavio Zavala Castro[1] **and Hung-da Wan**[1,2*]

[1] Department of Mechanical Engineering, The University of Texas at San Antonio, San Antonio, TX, United States
[2] Center for Advanced Manufacturing and Lean Systems, The University of Texas at San Antonio, San Antonio, TX, United States

[*] **Correspondence:**
Hung-da Wan,
hungda.wan@utsa.edu

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Managing a three-dimensional (3D) printing facility was found to be more challenging than using the technology. Our research laboratory provides 3D printing services to students and faculty who need the technology to fulfill their education or research objectives. Students enrolled in Senior Design classes, in particular, rely on the availability of services to support their capstone projects. While demand increases, the laboratory becomes less efficient and sometimes chaotic. To improve the operations, Lean Six Sigma methods were applied to enhance effectiveness and efficiency. Through a DMAIC project, we enhanced the availability of resources for requestors and prevented delay or accumulation of work. The new operating procedures enabled the laboratory to provide quicker services with fewer mistakes. This case study demonstrates that Lean Six Sigma is not only useful in manufacturing but also in research and educational settings.

Keywords: lean six sigma, DMAIC project, 5S, visual control, standardized work

Introduction

In years, the use of three-dimensional (3D) printing technology has been booming in many areas. Fields like manufacturing, medicine, and especially education have incorporated it with great success (1). The popularity of using 3D printing in engineering education comes from the simplicity of its operation, compared to traditional machining processes, and the spontaneous delivery of results, which has a significant impact on the learning experience (2).

This advantage is particularly reflected in the capstone projects, for which the engineering students develop and present their own designs in the final year of the engineering curriculum (3). With originality and innovation, the students create various designs to be prototyped to prove the concepts. Oftentimes, the engineering students choose to prototype their computer-based design models through 3D printing. As a result, a well-managed 3D printing laboratory is important for engineering education.

Within our academic department, a research laboratory was in charge of managing department-owned 3D printers in order to provide 3D printing services to students and faculty who were in need of the technology to fulfill their education or research objectives. This laboratory manages multiple 3D printers, including Dimension SST 1200es and Mojo, with similar design frameworks (4).

The 3D printing technology used by all the printers is the fused deposition method (5). Consequently, the printing materials being managed by the laboratory staff are mainly ABS and the soluble support material. As a well-known problem, the soluble support material deteriorates rapidly over time when exposed to the air. Therefore, material handling usually requires extra time and management efforts (3).

Initially, the operations of the laboratory were manageable when the number of requests for the 3D printing service was not too high. However, over the past decade, mechanical engineering has become one of the most popular college majors in the United States. According to the American Society of Engineering Education, enrollment of mechanical engineering students increased from 91,856 in 2009 to 135,672 in 2018, with a 47.7% growth (6).

A similar trend was experienced in our academic department, and due to the increased demand for 3D printing services, deficiencies and even chaos were observed in the laboratory's operations. With an urgency to improve the operations of the laboratory for higher efficiency and effectiveness, we initiated an improvement project that incorporates Lean Six Sigma methods to reduce non-value-add activities, streamline the process flow, and create a better work environment.

Originating in the manufacturing sector, Lean Six Sigma methods have been proven effective in various settings, including education (7). With the use of Lean Six Sigma tools, we expected to enhance the availability of resources for students and faculty and also prevent the accumulation of work or delays.

After carefully studying the operations and observing the observed issues, new guidelines and operating procedures were developed to improve efficiency and effectiveness. Under the new procedures, the laboratory is able to provide quicker services with fewer mistakes.

This case study demonstrates that Lean Six Sigma is not only a useful methodology in manufacturing settings but is also useful in research and educational settings. The goal of this paper is to provide documentation of our practical experience with Lean Six Sigma applied in an educational setting and to help readers in similar situations gain insights into what actions are available and viable. The following sections illustrate the methods used in this study as well as the results.

Methodology for process improvement

Lean Six Sigma has shown great impact on the operations of various systems and is definitely effective in higher education (8). One of the most popular problem-solving methodologies in Lean Six Sigma is the DMAIC methodology, which is an acronym for a five-phase procedure explained below (9):

- D: Define the goals of the improvement activity.
- M: Measure the existing system.
- A: Analyze the system to identify ways to eliminate the gap between the current performance of the system or process and the desired goal.
- I: Improve the system.
- C: Control the new system.

DMAIC is a data-driven quality strategy used to improve processes. It is an integral part of a Six Sigma initiative, but in general, it can be implemented as a standalone quality improvement procedure or as part of other process improvement initiatives (10). We can use DMAIC to follow well-defined steps to make operations more effective and efficient.

However, DMAIC only defines the overall procedure for problem solving. For specific problems, we need other Lean Six Sigma tools to identify improvement opportunities and potential solutions. Based on the types of issues observed earlier in the laboratory, the following methods have been selected by the project team for improving the operations of this research laboratory:

- SIPOC diagram
- Why-Why diagram
- 5S Method from Toyota Production System
- Standardized work
- Total productive maintenance (TPM)

More information about the selected tools will be explained in the following sections.

DMAIC—define phase

Project definition

The first phase of DMAIC is to define the problem, the objectives, and the scope of the project. This project emerged because there is an urgent need to make the 3D printing process in the laboratory more efficient by avoiding mistakes and delays. The laboratory primarily focuses on helping undergraduate students who are enrolled in the senior design classes, as well as researchers and teachers. By printing their designs, students and researchers can conduct tests on the prototypes.

With this project, we are looking to reduce the time of the process, maximize the use of resources provided by the faculty, as well as prevent the accumulation of work. The following areas of improvement have been identified as the scope of the project:

- General arrangement and organization of the facility
- Material management
- File management
- Machine maintenance
- Standard procedure for future operators

SIPOC diagram

SIPOC is an acronym for Supply-Process-Input-Output-Customer, which uses lists and flowcharts to visually define a system (10). To understand the scope and general operations, the SIPOC diagram was used in this study to identify all relevant elements involved in the process. The diagram

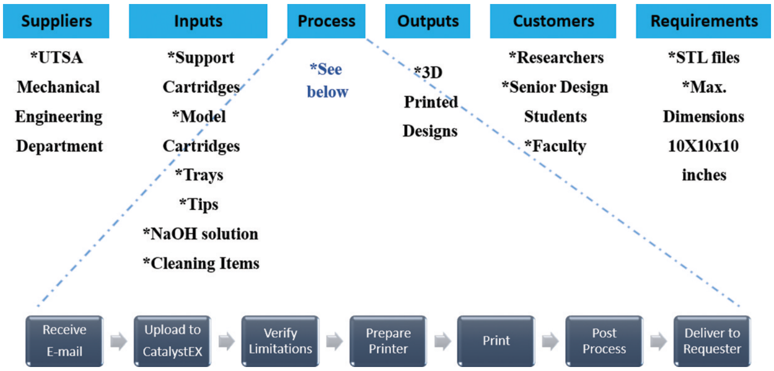


FIGURE 1 | SIPOC diagram of the system.

explains, in a simple and visual manner, the participation of all parties as well as the steps of the process, and it has been a preferred tool in the define phase of many Lean Six Sigma projects (11).

As shown in **Figure 1**, the supplier of this system refers to all students and faculty of the department who need to use the 3D printing service. The inputs are all of the materials that the suppliers provide. The main process is explained in a brief way in the diagram, as are the steps being followed during the printing process.

The outputs are the final products, i.e., the 3D-printed parts. The customers are again the students, researchers, and instructors who request to use the service. In addition to the SIPOC, a sixth part, "Requirements," was added to the figure. It describes the specifications required for a printing job.

DMAIC—measure phase

The main objective of the "measure" phase is to identify the current state of the system. For this purpose, the following information has been collected:

Number of printing requests

To understand the workload of this research lab, the number of job requests from the year before the project was summarized. We divided this information into two charts: one for the demand of each month (**Figure 2**) and the other for the types of clients (**Figure 3**).

As seen in the charts, most of the jobs are requested by students, followed by researchers, and finally by faculty (instructors). In comparison, the fall semester has fewer print jobs required. The demand was more stable throughout the spring semester, due to the fact that more students start their 2-semester Senior Design classes in the fall semester. When they get into the spring semester, many of them have their designs mature enough for prototyping early in the semester, and they also want to use the 3D printer early to avoid competing for the resource later in the semester.

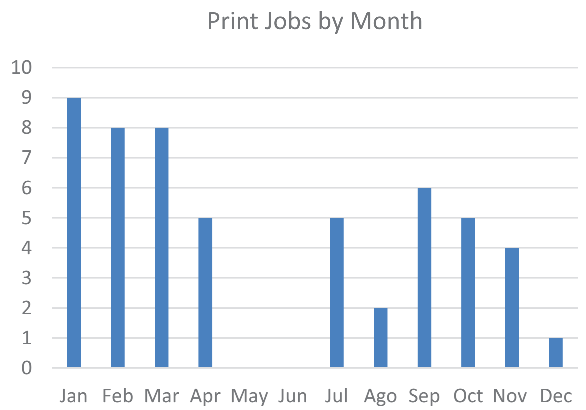


FIGURE 2 | Use of 3D printing services by month.

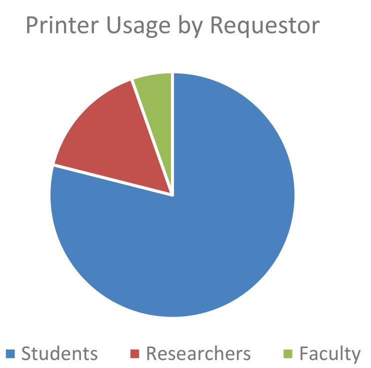


FIGURE 3 | Use of 3D printing services by type of requestor.

Process flowchart

From the previous operations, we have observed that the process had not been well defined, so the lab assistants did not have standards to follow. Therefore, there had been delays, miscommunications, and some other issues. In order to display the decisions and actions taken during the process in a more effective way, we created a flow chart in which we can observe the different variants that may arise from each action. As shown in **Figure 4**, this chart indicates the points that may be causing conflicts, which helped us identify where lean manufacturing tools can be used to improve the process.

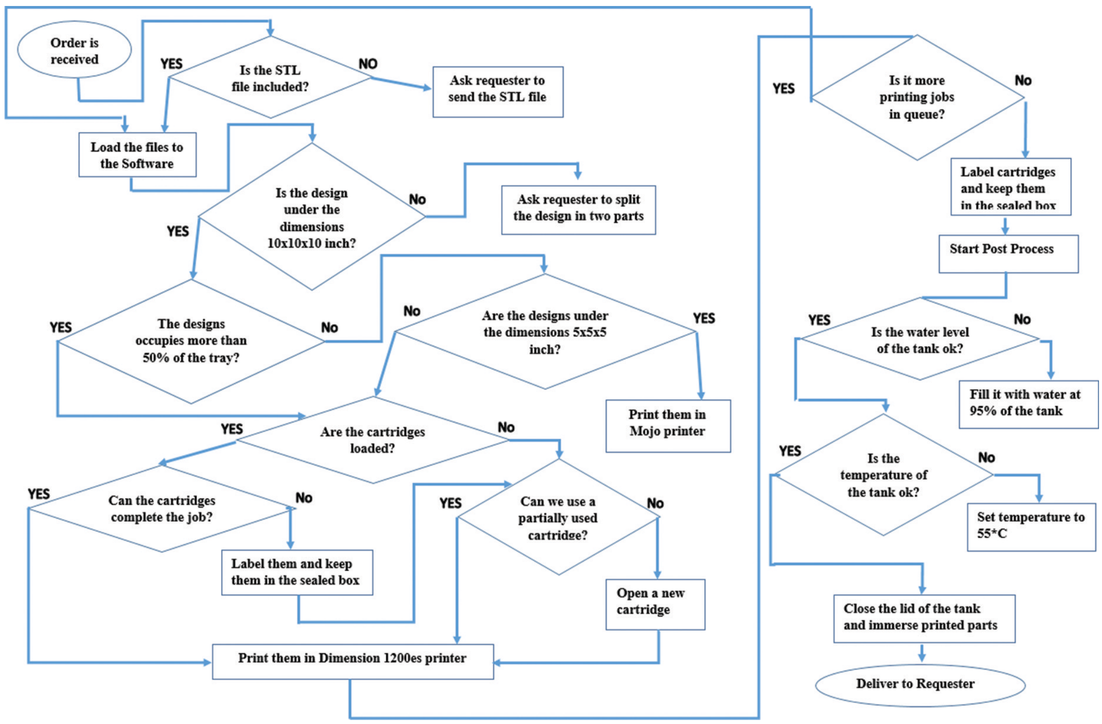


FIGURE 4 | Detailed process flowchart to show all decision points.

With the flowchart, we can clearly see each procedure to follow throughout the process, from when the order is received until it is delivered to the requester. We observed that there are 10 points where it is necessary to take a decision and 12 actions that can be taken as responses to the variants.

This flowchart has a small cycle where, after printing the designs, it asks if there are more pieces pending to be printed. If the answer is affirmative, the cycle will begin again. This tool illustrates that we must take greater care before printing the pieces because it is at this point that most of the decisions are made in comparison to the post-printing part.

DMAIC—analyze phase

The spirit of the "Analyze" phase in Six Sigma is to identify the root causes of the problems. Therefore, in this phase, we utilized the Why-Why diagram (10) to identify the potential causes of different operational areas in order to develop countermeasures in the next phase. As shown in Refs. (12) and (13), the why-why analysis can be performed in a variety of formats, including the 5-why method, a fishbone diagram, or in tabular form. Here, we used the tree-diagram format to identify the multiple root causes for each issue.

Material handling

First, the handling of printer cartridges (raw materials) had been a serious issue in the operations. Material handling was one of the objectives outlined in the project charter because we have observed a repetitive problem with the accumulation of partially used cartridges.

Using the Why-Why diagram, as shown in **Figure 5**, we found a few different causes that resulted in the accumulation of cartridges. Later in this paper, the countermeasures to prevent the accumulation will be developed.

As shown in the diagram, the first cause is the defective material. Exposure to moisture caused the cartridges of support material to harden. Because of the material's hardening, bubbles were created during the printing process. These bubbles in the soluble support material create instability at the moment of printing the designs.

They may also cause problems with the nozzle head of the printer. The nozzle head is the part responsible for heating the material, and due to these bubbles, it can get stuck at the moment that the machine tries to extrude it.

Another cause of the accumulation of the partially used cartridges, as shown in the Why-Why diagram, was the schedule of the operators. The average time for the printer to complete a job is 20 h. Sometimes, it is difficult to follow the correct procedures to wrap up the process immediately after the printing is completed, because this may happen very late, very early, or during the weekend.

The last cause that may be creating the accumulation of the cartridges is the operator's ignorance of the percentage of leftover contents in the cartridges. For the operator, it is easier to open a new cartridge instead of looking for partially used cartridges that can complete the job without a changeover. These causes have been captured in **Figure 5**.

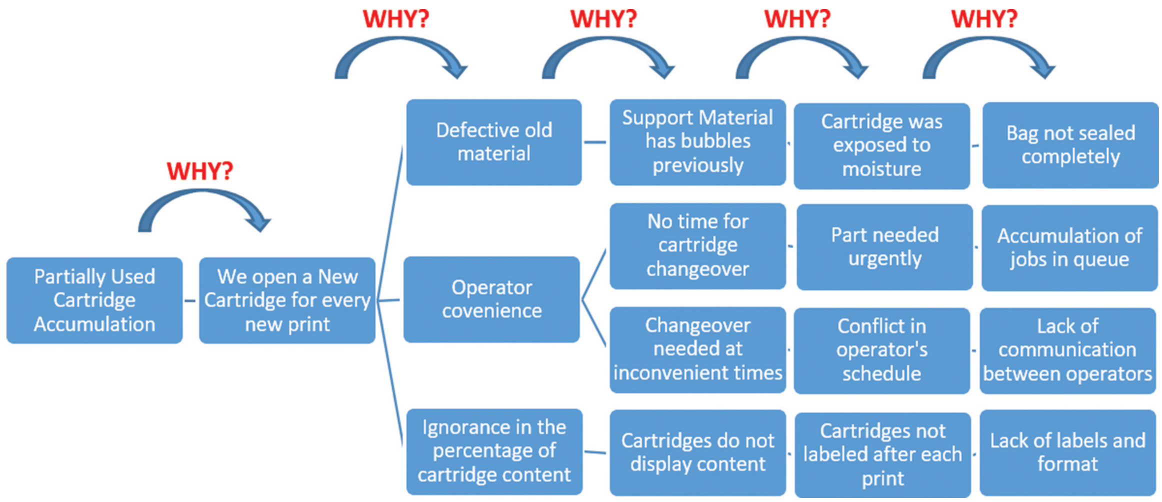


FIGURE 5 | Why-Why diagram for causes of cartridge accumulation.

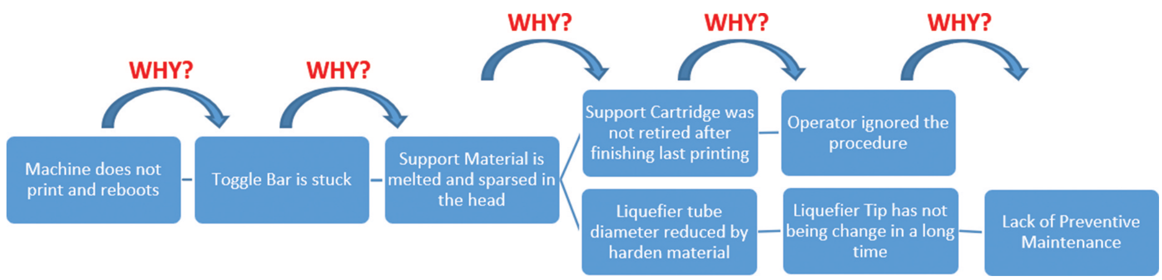


FIGURE 6 | Why-Why diagram for causes of machine malfunction.

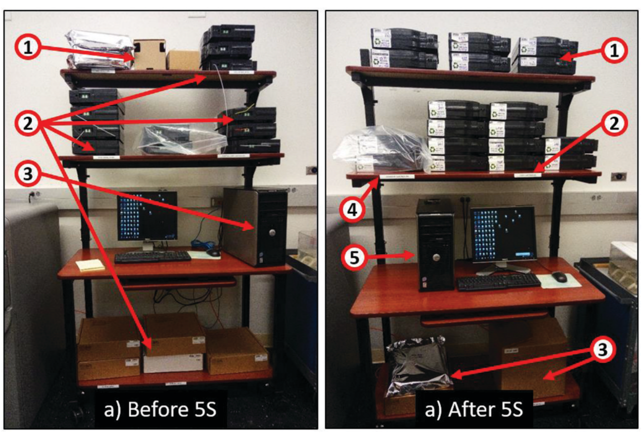


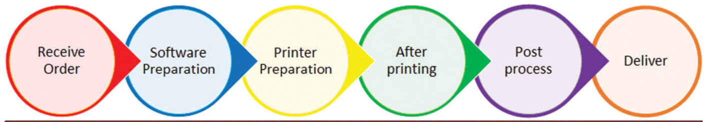
FIGURE 7 | 5S implementation in computer area.

FIGURE 8 | 5S implementation in cabinet area.

Machine maintenance

Another improvement area identified for this project is machine maintenance. In the previous semesters, we encountered a serious mechanical problem with the printer where the toggle bar was stuck. As shown in **Figure 6**, a Why-Why diagram was used to determine the causes of this problem.

Based on the diagram, we found two root causes that may have created the mechanical problem. The first is that the operator ignores the procedure and does not know that the support material can be heated and melt even when the machine is not printing. The second cause for this problem is that there is no preventive maintenance program, and thus the liquefier tip has not been changed in a very long time.



Receive Order
1. Download files
2. Verify for the number of copies for each STL file with the requester
3. Copy the STL file to the assigned folder and change the name by adding the name of the requester at the end.
Software Preparation
4. Load files to Dimension software
5. Verify dimensions of the part (10 in x10in x 10 in)
6. Change orientation to save support material
7. Verify the pack container occupies more than 50 %
8. Verify there is no previous jobs in the queue
9. Push print button in the software
Printer Preparation
10. Verify if model and support material is loaded (model top, support bottom)
11. Install tray and secured it.
12. Fill control table for every tray and new cartridge used.
13. Purge Container.
14. Push print button in the printer
15. Verify support material is not creating bubbles
After Printing
16. If there is no more jobs in queue take out the cartridges
17. Label cartridges to show the remaining content.
18. Put current cartridges in the sealed box to prevent moisture
Post Process
19. Remove tray from printer
20. Verify there is no fragile parts to be removed from the tray
21. Remove part from tray in the plastic box
22. Immerse the part in the solution tank and close the lid
23. Verify the water level of the tank (must be almost full)
24. Verify temperature of tank 55*C
Deliver
25. Send an email to the customer to let him know his design is ready and establish the time of the meeting in the lab SMS lab 2.232 AET building.
26. Using gloves take out the part from the tank
27. Immerse the part in a clean water container
28. Dry it off with the paper towel
29. Take a picture of the design printed.
30. Deliver to Requester.

FIGURE 9 | Standardized operating procedure in six stages.

File management

For this project, another area for improvement has been identified as the file management. This is because there was no control over the files loaded onto the computer managing the 3D printers. While it is true that all the files can be retrieved by searching the archived emails, which is how we receive the orders, it is also true that during the communication between the requester and the lab staff, the STL files for printing can be confused, ignored, or lost.

When an order was received during the current process, the STL files were downloaded from the email and then copied to the computer in the printer desk or onto a flash drive. However, there is a lack of control over the files received. If the files sent cannot be printed at once, some files are left pending, and because of the lack of control, a second operator needs to download the files again, creating a rework.

Since the causes of the file management issues were more straightforward, the project team did not develop a Why-Why diagram for them but recorded the potential causes directly. Following the identification of potential root causes of various issues, the next Six Sigma step is to improve the operations by developing countermeasures.

DMAIC–improve phase

After the root causes of the issues were identified in different areas, the project team decided to address these causes by implementing lean tools, including 5S, standardized work, and total productive maintenance (TPM) (14). The results of the implementation have been summarized as follows:

5S implementation

In the analysis phase, we found the causes that are generating the accumulation of cartridges, but we needed to find a way to control the problem that already existed. We decided to apply the Toyota Production System's 5S tool in the laboratory, which is expected to help reduce waste and control materials in a systematic way (15).

The 5S is a methodology to help develop a quality work environment, both physically and mentally, through

Recurrence of each maintenance:

- Every Print (blue)
- Every Month (red)
- Every Semester (yellow)
- Every Year (green)
- When needed (black)

Purge Container:

1. Lift up on purge container to release it
2. Pull container towards you.
3. Empty container and reinstall on the three mounts, ensuring it is flush with the chamber wall

Tip Area Clean Up

1. Enter Head maintenance (tips can be hot)
2. Press Maintenance, press Head and Press Head Maintenance
3. Use leather gloves to avoid burns
4. Clean FOD around tips using needle nose pliers
5. Exit maintenance

Inspect Teflon shield

1. Remove heat shield by removing bolts on either side of heat shield
2. Check the shield for any damage, any material trapped between shield and cover, and to ensure adhesive is still firmly attached to the cover.

Replace Teflon shield

1. Remove old shield including excess adhesive and modeling material from mechanism
2. Remove protective strip on new shield
3. Put new shield inside cover making sure it is centered on the intersecting cut line
4. Press new shield in place and inspect for solid adhesion

Removing debris buildup:

1. Remove foreign object debris located in the bottom of the build chamber using a vacuum.
2. Remove foreign object debris located in the modeling base.
3. Clean the glass with glass cleaner or a brush.

Clean Fan Filter

1. On back of machine snap off the fan filter frame
2. Remove filter by pulling out.
3. Clean filter with soap and water
4. Let fully dry before reinstalling
5. Reinstall filter

Liquefier Tip Removal

1. From Idle select Maintenance, Machine, Tip, Replace
2. After temperature stabilizes printer will display: Tip Maintenance-Replace tips
3. Open glass door and remove plastic head cover using squeeze tabs on each side.
4. Use 7/64" Allen wrench to loosen the 4 tip screws 4 full turns
5. Grasp stainless shield with needle nose pliers and pull out and down to remove tip
6. Repeat steps 4-5 for 2nd tip.

Tip Installation

1. Install heat shield with Teflon washers and retaining screws
2. With leather gloves inset new tip into heat block
3. Pull the tip shield toward you with needle nose pliers and lift up to install
4. Once tip is against heater block push the tip towards the back of the machine.
5. Verify the tip is seated correctly leaving a space in between.
6. Use 7/64" Allen wrench to firmly tighten heater block clamp screws
7. Repeat steps 2-6 with 2nd tip
8. Re-install plastic head cover
9. Select Yes on display screen
10. Printer will now display "load model"

Inspect/Replace brush/ Flicker Assembly

1. Power Down the printer
2. Push toggle head to the left of the machine
3. Lift assembly up and the out. Discard assembly
4. Place a new assembly into slot and make sure it is fully seated.

Axis lubrication

1. Clean the z axis drive screw, x axis guide rods, y axis guide rods and z axis guide rods with **isopropyl alcohol** and a clean shop towel
2. Put on impermeable gloves
3. Sparingly apply **ktrytox grease** to the cleaned locations making sure not to get the grease on

Tip Shroud Replacement

1. Enter Head maintenance. From idle, choose maintenance.
2. Press next, press head maintenance.
3. Warning: head area is hot handle with leather gloves.
4. Using the putty knife, position the blade between the tip shroud and the tip shield.
5. Using the putty knife blade, separate the tip shroud from the tip shield
1. Using a wire brush clean the tip to remove any debris
2. Install new tip shroud by pushing it over the exposed tip, making sure its fully seated against the tip shield
3. Exit maintenance.

Replace Chamber lights

1. Power down printer
2. Disconnect lights from wire harness
3. Remove 3 screws attaching the lights
4. Install replacement light being careful not to overtighten screws.
5. Re-attach wire harness.

FIGURE 10 | Defined tasks for total productive maintenance.

#	Maintenance		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Removing debris buildup	Initials												
		Day												
2	Update Excel Printing Record	Initials												
		Day												
3	Tip Area Clean Up	Initials												
		Day												

#	Maintenance	Frequency	Fall	Spring
4	Solution tank changeover	Every 3 months		
5	Axis lubrication	Every semester		
6	Inspect / Replace Teflon shield	Every semester		
7	Inspect/ Replace brush (flicker assembly)	Every semester		

#	Maintenance	Frequency	20__	20__
8	Inspect / Replace Tip	Every year		
9	Clean Fan Filter	Every year		
10	Tip Shroud Replacement	Every year		

FIGURE 11 | Tabular form designed for total productive maintenance.

five actions: sort, set in order, shine, standardize, and sustain (14). The 5S philosophy applies in any work area and has been an important method to develop a visual workplace (16).

In the laboratory, we have three spaces designated to the 3D printing process: the computer desk, the post-processing tank, and the cabinet where the materials and tools used in the printer are kept. 5S was implemented in these areas with very satisfactory results. Below, these results will be explained in detail, showing the progress of each area.

The computer desk area is next to the printer and is where the computer is located. The CAD designs are sent to the printers from this computer. This desktop is divided into four sections, and in three of them, cartridges are stored at different levels of content. The following issues were identified, as shown in **Figure 7a**:

1. Unnecessary items: Empty boxes in the top shelf
2. Accumulation of material: Empty, half, and full cartridges were mixed in the same area
3. Unsafe location of computer: The computer was located on the edge, next to the post-processing tank, exposed to splashing

After implementing 5S, the locations of different items are defined and standardized with labels to ensure all operators know where to keep the materials. **Figure 7b** illustrates the results after 5S with the following improvements:

1. Support material was cataloged from lower to higher level of contents.
2. Model material was cataloged from lower to higher level of contents.
3. New cartridges and trays were located in an accessible location.
4. Current cartridges were kept next to the printer.
5. The computer was relocated away from the edge near the tank.

5S was also implemented in the cabinet area. In this area, we stored all of the materials and new cartridges. 5S helps to maintain order and control of the items. As shown in **Figure 8**, all shelves are now clearly labeled to standardize the locations of supplies, tools, and accessories.

Next, 5S was also implemented in the post-process tank area. The post-processing tank is the last step in the 3D printing process, where the support material is dissolved. Implementing 5S makes the area cleaner with standardized locations for tools and supplies. It significantly reduces the time it takes the operator to locate the required items.

Finally, 5S was also implemented on file management in the printer computer, which stores all the print job requests and associated STL files. The major change was to separate the STL files from other files, and then we created folders that specified the time in which they were printed.

When the operators receive an order, they will now follow a new procedure to rename the STL files and save them to the specified folder. With the 5S implementation, it would be easier to keep track of the job requests and locate the files.

Standardized work

As emphasized in the verb "standardized work," the heart of this method is an active process for the organization and specification of uniform work steps to be performed (14). The best practices to develop a standardized work procedure are to use visual aids (17). As identified in the Why-Why diagram, the operator often did not know the procedure clearly.

Therefore, the project team designed a checklist with all of the steps of the process. This checklist is an effort at standardizing the work so that we can ensure the operators know the right procedure at any time. As shown in **Figure 9**, this list was divided into six stages, and a color was assigned to each of them to make it easier to read and understand.

Another action taken in order to solve one of the root causes of the problem of the material sticking, based on the Why-Why diagram, was the use of a new sealed box. The partially used cartridges used to be stored in sealed bags to prevent moisture; however, these bags were sometimes not completely closed, and they tended to tear after use. By substituting the bag for a sealed box as a new standard, it is possible to store more cartridges at the same time, and they will be more durable.

Total productive maintenance

TPM is a holistic approach to developing and maintaining equipment and process reliability that involves all personnel acting together to control and improve their workplace (14). TPM emphasizes proactive and preventative maintenance to maximize the operational efficiency of equipment. It blurs the distinction between the roles of production and maintenance by placing a strong emphasis on empowering operators to help maintain their equipment.

For the problem of the support material sticking in the printer, we found that one of the root causes was that there was no preventive maintenance in place. Therefore, as shown in **Figure 10**, we developed a standard procedure with a checklist that describes the steps required for every maintenance task to keep the machine in an optimal state. A corresponding paper form, as shown in **Figure 11**, was created to track the time of the maintenance tasks, which also serves as a reminder for future tasks.

DMAIC—control phase

The spirit of the control phase is to sustain the results and prevent the previous problems from happening again (18). To have control over this process, several tabular forms similar to **Figure 11** and some checklists have been developed in order to enforce the new standard operating procedures.

1. Tabular form for printer desk material control
2. Tabular form for cabinet material control
3. Tabular form for maintenance control
4. Maintenance steps work sheet
5. Checklist of printing process

Additionally, we started using online document storage to make the information available in real time to all staff members. The communication between operators is greatly improved as a result of this initiative. Now everyone knows exactly which steps of the requested jobs have been completed and which are pending.

Conclusion

In this case study, the DMAIC methodology was adopted to guide the improvement project. Different Lean Six Sigma tools were applied at every phase of this methodology, following the logic to describe the process and issues, understand the gaps, and solve the problems. New forms and procedures were created to control the operations, from materials handling and data management to printing and maintenance, so that the improved performance would be sustained.

The main improvement made in this project was the reduced time and effort spent on managing the print jobs, raw materials, and equipment. This improvement is essential, as students and researchers need their prototypes as soon as possible to conduct their research. Now we are able to deliver the results in a timely manner and within a more predictable timeframe.

This case proved that the Lean Six Sigma tools are as effective in a small 3D printing laboratory as they are in large companies. By using this methodology, we were able to identify the problems, solve them, and control the results in a systematic way.

The goal of this paper is to present a case study that provides insights into practicing Lean Six Sigma in the setting of an educational and research environment. Despite the fact that this paper contains no theoretical breakthroughs or technological innovations, we hope that the lessons learned and experiences gained from this improvement project will be useful to other Lean Six Sigma practitioners in similar situations. We also hope this paper will encourage more Lean Six Sigma practitioners in other sectors to share their successes.

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