Lean Six Sigma Process Improvement at Headwall Photonics

Major Qualifying Project Submitted to the Faculty of

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Submitted by:

Caitlin Boermeester
Johann Bradley
Carson Brooks
Kaitlyn Hess
Kayla Legatt

Sponsor:

Headwall Photonics

Advisors:

Walter T. Towner, Jr. Ph.D.
Selcuk Guceri, Ph.D.

Abstract

The purpose of this MQP was to evaluate one of Headwall Photonics current cleaning processes and present recommendations for process improvements at their manufacturing facility in Fitchburg, Massachusetts. The objective of this project was to reduce the scrap rate, improve repeatability, and reproducibility in the pre-clean process for Headwall Photonics. The rationale behind this was that Headwall's current pre-clean process was inconsistent and experiencing high scrap rates.

The methods utilized began with collaboration from subject matter experts at Headwall to better understand and define company parameters of what to optimize in the cleaning process. Scrap rate, reproducibility, and repeatability were three key parameters identified to improve in the cleaning process. Additionally, when examining the whole process of manufacturing gradients, an improved design for fixture was identified as a way to mitigate scrap rates.

Due to the fragile nature of these products during manufacturing, a standardized process that is poka-yoke ("mistake-proof") in its design is critical in order to mitigate waste in the process. The project's first step to understanding how to achieve our objective was to use axiomatic design (AD) decomposition. Further, generating a value stream map of the process to identify bottlenecks and assemble a value-effort graph allowed us to choose favorable alternatives to improve the given optimization parameters.

Next, our team directly simulated Headwall's current pre-clean process in a lab-based environment at WPI in order to compare their current process with a proposed alternative that may improve scrap rates. The success of each cleaning process was evaluated through contact angle measurements and cost-benefit analyses. One of the methods explored included the use of carbon dioxide, while another utilized plasma technology to clean the surface of the substrate.

The results of our experiments with varying the pre-clean process were that the CO_2 process was more efficient but the results were not consistently better than Headwall's original process using an acetic bath. The plasma cleaning experiment is still underway at the Plasma Institute at Drexel University, but initial evaluation indicates that this method could potentially prove beneficial to Headwall's pre-clean process if they chose to incorporate it.

Additionally, the new fixture design for the final efficiency test incorporated a spring mass system that will decrease the chance of defects at the step in the process. This fixture was developed through a series of design iterations and prototyping. It resulted in an improvement from the previous design in that it reduces the chance of an operator damaging the part during loading and unloading of the substrate.

To conclude, our team recommended Headwall continue with their current acetic acid process but incorporate lean process improvements to enhance effectiveness and efficiency. This project also identified a new cleaning method, plasma technology, that could potentially be used by Headwall Photonics in the future. Lastly, a series of recommendations was made, including an improved process map and work instructions, that will improve performance for the pre-clean aspect of Headwall's manufacturing process.

Acknowledgements

Our team would like to thank Headwall Photonics for their generosity and contribution to this project’s overall success as well as our advisers, Professors Walter Towner and Selcuk Guceri for their guidance and development throughout this project. Without the assistance from both of these parties, our team would not have been able to conduct this project and present our discoveries today.

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1. Introduction

This is a Major Qualify Project that consists of a partnership with Headwall Photonics to develop process improvement recommendations that meet company standards and are repeatable and deployable as a standard operating procedure. This project specifically focused on quality improvements in the manufacturing process of what we will call for the purposes of this project "Gompei's Grating" as well as the overall photolithographic process prior to alignment and development. for Headwall Photonics, a hyperspectral imaging company with facilities in Fitchburg, Massachusetts and Bolton, Massachusetts. As a group, we focused on developing a standardized flow of production minimizing any Non-Value-Added Time (NVAT) by using the axiomatic design method while also mechanically producing a Quality Control (QC) tool that can be used throughout the process to track and define defects to determine root-cause analysis. Additionally, the group developed an improved means to track product throughout manufacturing to assist in future supply chain internal lead time projections.

2. Objective and Project Goals

The objective of this project was to develop an improved result in scrap rate, repeatability, and reproducibility in the pre-clean process for Headwall Photonics. We will be using multiple engineering disciplines to synthesize development in the process and in the technical design system. In accordance with these objectives, the following goals were determined based on the guidance from Headwall as well as the analysis conducted by the team:

1. Using the axiomatic design method, we developed a standardized process for the manufacturing of the substrates prior to their alignment and development. Additionally, this process will be replicated for the entire Gompei Grating manufacturing process in order to effectively reduce the scrap rate in the process. Key tasks associated with this goal is to mitigate waste in the process and present recommendations for process improvements throughout the process.
2. Evaluated a QC inspection tool that can be utilized throughout the manufacturing process in order to effectively determine deficiencies in the product to determine effective root cause analysis. Key tasks associated with this goal are to develop a tool that does not require white light to be able to visibly show deficiencies in the substrate to the human eye. This process will also involve an incorporation period into the process as well as experimentation to confirm tool accuracy.
3. Developed product tracking methods that can be applied throughout the manufacturing process. Key tasks associated with this goal is to develop a means to track the products in order to effectively identify, track, and project product yield.

3. Background

3.1. Headwall Photonics

The company we partnered with for this project is Headwall Photonics. Headwall was founded in 2003 to provide "spectral solutions" no other company offered (Headwall, 2020). Although based in Massachusetts, Headwall has a facility in Belgium and partners in Europe, Asia, and South Africa. Headwall is a company that focuses on "integrated hyperspectral imaging solutions, spectral imaging sensors, raman imaging instruments, and differentiation gratings and optical modules for OEM applications" across four markets (Headwall, 2020). The markets Headwall focuses on are "remote sensing, machine vision, medical biotech, and defense government" (Headwall, 2020).

3.2. Axiomatic Design

The axiomatic design (AD) method was used to look at the entire system and understand all parts of the problem occurring. The goal and main use of axiomatic design was to have a product or process become better, faster, and cheaper. It enabled the whole team including the sponsors and advisors to be on the same page regarding project goals and identifying solutions (Brown, 2013).

The first step in axiomatic design was to determine the customer needs. From here, the goal was to identify the functional requirements (FRs). Then we identified the design parameter (DPs), which is the action that helps to achieve your functional requirements (Brown, 2013).

Axiomatic design helped to create a common understanding of a process, goals, and necessary requirements through creating matrices which enabled the team to see the whole picture and avoid unnecessary iterations.

3.3. Value Stream Mapping

Value stream mapping is a flowchart tool used to document steps in a process. A very common tool used in lean practices, value stream mapping helps to identify waste and process times. Value stream mapping helps teams and organizations develop process improvement plans to become more efficient (ASQ, 2020).

3.4. Lean Manufacturing

3.4.1. Pull System

In lean manufacturing, there are different systems in order to have organized inventory in order to reduce waste during the production process. Two systems that are commonly used are push and pull systems. A push system keeps items in stock, thus increasing holding costs and pushing inventory to keep customer demand. Whereas a pull system minimizes storage costs, minimizes losses on products not sold, and costs less upfront investment for inventory (Stevens, 2020). A pull system is demand driven leading to products being manufactured as they are ordered.

3.4.2. Data Driven Decision Making

Using data to backup decision making along with background knowledge is a great way to determine results. In the project, Gage R&R (gage repeatability and reproducibility) is a process our team used to drive decision making and help Headwall become a more efficient and effective company. Repeatability and reproducibility study is “a study of variation in a measurement system using statistical analysis” (Evans & Lindsey, 2020). Gage R&R helps to reduce the variation in a process by determining where the variation is coming from “variation of the process itself and the variation of the measurement system”, the operator or actual process and adjusting accordingly so variation is decreased (Gage R&R, 2021). This also means having a standard process for training operators, so they are all familiar with how the operation or process should run.

3.4.3. Standardization for Efficiency

A ‘traveler’ which can be paper or electronic is a method of tracking a process at Headwall. It includes a variety of metrics that an operator has to fill out while completing the steps of the process. Our team’s goal was to review the traveler and standardize it to ensure that it was easy to understand for operators, it did not have unnecessary spots for data, and that the process of using the traveler was as simple as possible through standardization. This type of standardization enabled Headwall to have a more efficient and effective system and stronger productivity.

3.5. Statistical Process Control

In any industry, data drives all process improvements and what makes the difference company-to-company is how this data is both interpreted and executed upon. The use of Statistical Process Control is a method that was incorporated into the current production system at Headwall. In this, data tracking was utilized from a previous intern’s summer work to design an interactive dashboard. This dashboard displays Key Performance Indicators (KPIs) and updates automatically to show current production trends to make corrective measures as production trends to different ends of the product specifications.

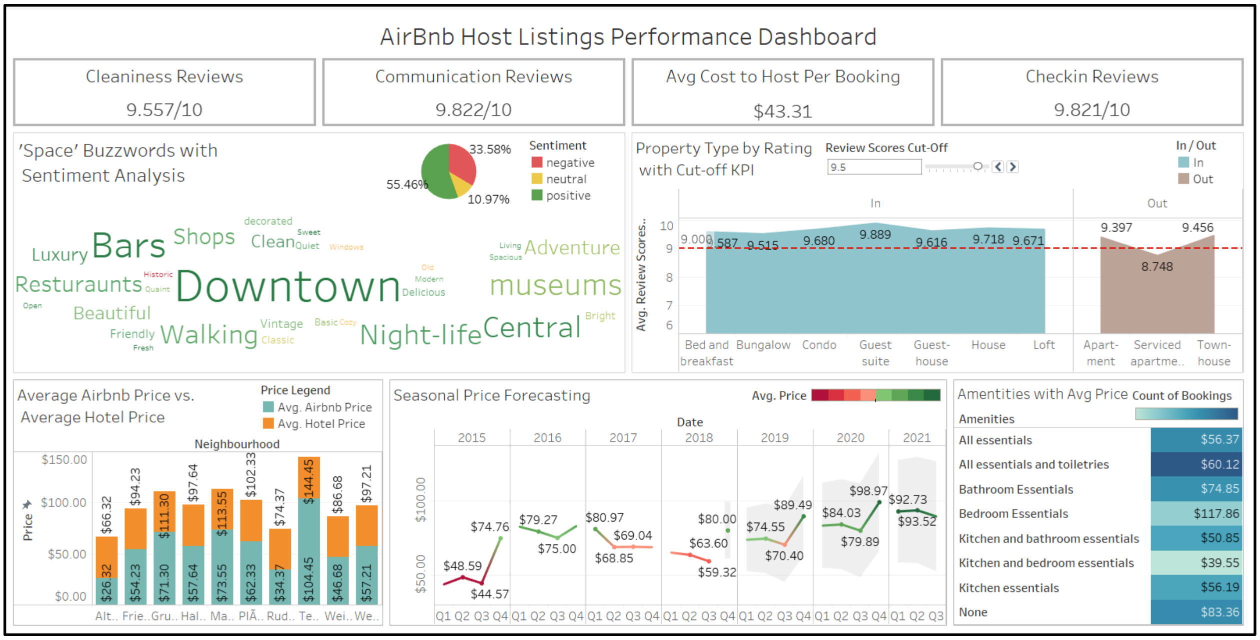


Figure 1: Airbnb Host Listings Performance Dashboard

An example of what this dashboard could look like is seen above. This dashboard was made for a final project in another WPI course, MIS 584: Business Intelligence using Tableau and was intended to assist Airbnb in improving their listings marketing on the app. (WPI.edu, 2021) This dashboard included sentiment analysis, forecast modeling, and identified key trends to assist hosts. Similarly, at Headwall this kind of use of data can be incorporated into the Gompei Grating's process. For example, batch by batch scrap rate can be projected with specific scrap deficiencies on a commonality list to be able to effectively identify which part of the process is causing the scrap rate in any specific area. Additionally, using this software trends can be forecasted further to understand where production is heading towards. What can also be useful for Headwall would be the use of "cards" (seen at the top of Figure 1 dashboard), to display current metrics and utilize color coding to signify performance. For example, if the scrap rate were to exceed 20% for one batch size, that value would turn red indicating there was an issue in this batch. This entire data wide process can be projected via television for all workers on the floor to see how the company is performing in their job. This incentivizes workers as well as shows what they are doing and why it matters for Headwall's success. Data drives everything in effective business decision making, and the use of this operational dashboard can assist with identifying defect trends in their manufacturing setup.

3.6. Computer Aided Design and Additive Manufacturing

Prior to the invention of advanced software systems, engineering the design of new parts was completed through handwritten drafting. Consequently, this process was time consuming and challenging to modify designs as these were physical drawings. These issues in engineering design combined with the subsequent need to have a more advanced platform for design is what sparked the demand for Computer Aided Design. The earliest traces of what we see as CAD today can be traced back to the late 1950s when Dr. Patrick Hanratty, a computer scientist at the time, developed PRONTO which was the first numerical control programming system (Beck, 2019).

Today, CAD is widely used in the engineering community to generate engineering drawings and models. CAD can come in many different software variants fitted for specific purposes (parts, construction, architecture, etc.). A few examples are SolidWORKS Autodesk Inventor, and Autodesk Revit. These softwares continue to follow traditional drafting standards, however function from a virtual platform to allow for quick modifications and a 3D modeling of a design.

Another emerging technology in the efforts of engineering design is the use of additive manufacturing to generate a 3d model in person to examine physically. This involves the export of these CAD files to a 3D printer that can support the dimensions of that drawing and can print the dimensions specified. This new way of modeling has allowed engineers to experience another perspective of modeling prior to manufacturing of a new item. Overall, these technological advancements in engineering design have paved the way to assist humanity in the advanced design of components.

3.7. Optical Lithography (Photolithography)

Technological advancements over time have developed a need to be able to imprint shapes within a glass substrate to be able to reflect light to a product's specific nature. Integrated circuitry and the overall function of computer chips encompasses primarily the market in photolithography as these products require light and energy to flow through these micro patterns which is why most laptops today are able to cultivate a slim design. Photolithography harnesses the means of light to transfer energy in specific geometric dimensions that are not visible to the human eye without proper instrumentation. These gradients are imprinted with a specific geometric shape which allows wiring to complete its circuit fulfilling its technological purpose.

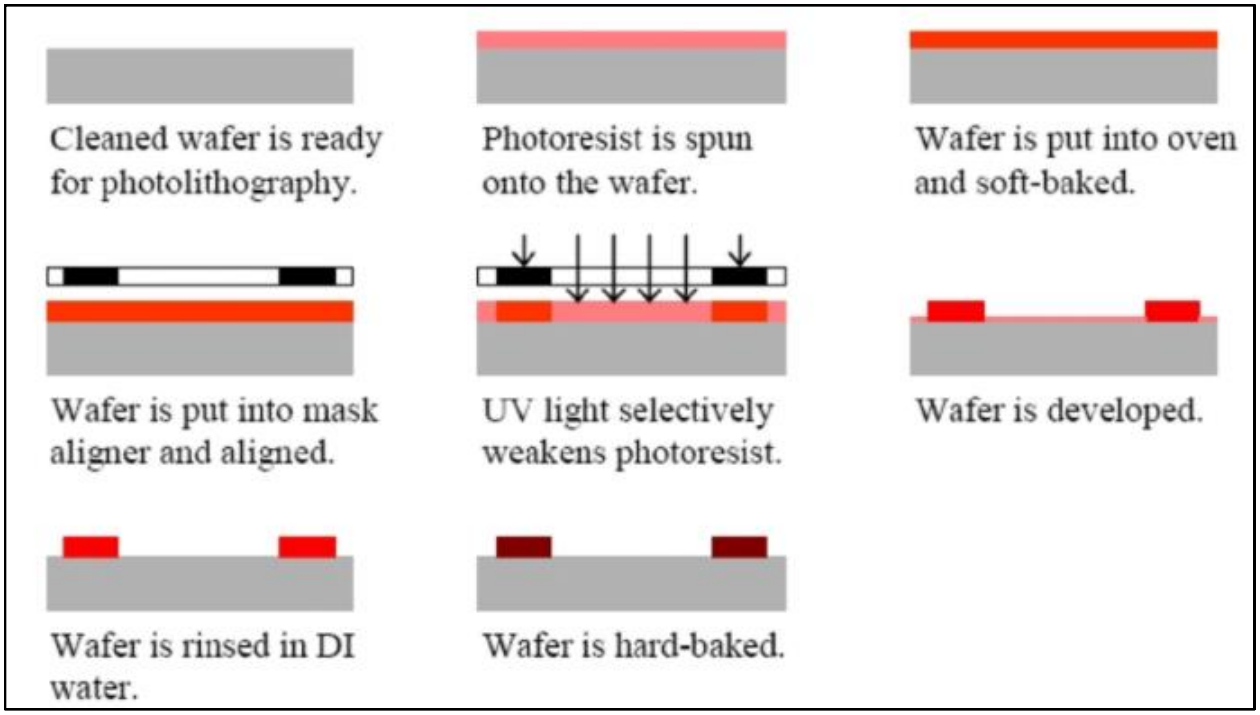


Figure 2: Photolithography development process (Balakrishnan, 2014)

The process of photolithography begins with a substrate (primarily glass) that is pre-cleaned prior to its movement to the photoresist process (Wafer World Inc, 2016). This cleaning process functions to remove any bio-material or outside particles to the substrate. This helps to minimize deficiencies in the geometric complexity when the substrate becomes developed. After this process, the substrate is moved to the photoresist spin which is a tool used to spin the substrate, so it is coated with an even layer of the photoresist. For the photoresist process, silicon dioxide is applied to the substrate to act as a barrier between the surface of the substrate and the photoresist chemical. There are two types of photoresist: positive and negative; a positive photoresist is when there is an exact copy of the photoresist pattern whereas a negative completes the exact opposite shape of the photoresist pattern. The application process for the photoresist material consists of spinning the substrate at a high RPM for roughly 30 seconds to one minute which assists in the even and balanced spread of the photoresist material across the substrate. After the photoresist material has been confirmed to be spread evenly across the substrate, the substrate is moved to soft bake where the substrate is set in an oven. The heat from the oven dries the photoresist material on the top of the substrate which allows it to become photosensitive or developed to a specific geometric complexity.

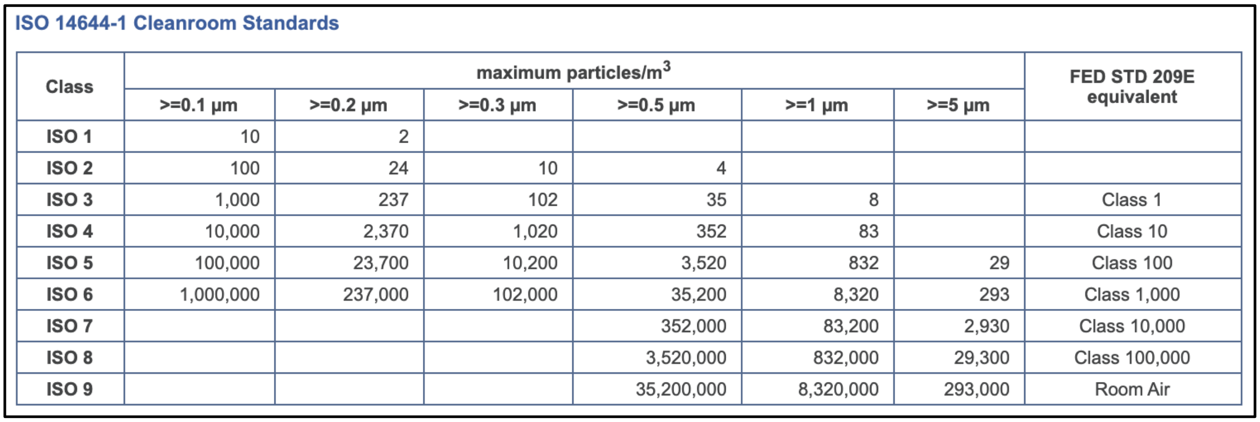
After the photoresist material has been added, the process continues to develop a gradient. In other words, to develop an item that shields lights or magnifies light as it passes through the material. This alignment process aligns the substrate to the proper dimensions specified and is then developed by shining a UV light directly through the substrate in order to form a gradient. After this process is complete, the product moves to a hardbake and final inspection of the product. The hardbake functions to stabilize the photoresist and once cooled, the product is ready for final inspection.

3.8. Context of a Cleanroom

A Cleanroom is a space where the environment is precisely controlled to limit particles such as dust, chemical vapors, or air particles (Clean Air Technology, Inc., 2021). They are used in various manufacturing and research settings where material is involved that could be affected easily by contaminants in the air - most commonly, Cleanrooms are used when dealing with semiconductors, optics, pharmaceuticals, or biology-related research. The reason this environment is safe for these sensitive products is that they are built in a manner that filters the air and drastically reduces the number of particles in the space, as well as controlling temperature, humidity, and air pressure. For example, the air outside in a typical city setting has roughly 35,000,000 particles per cubic meter that are larger than 0.5 microns in diameter (Clean Air Technology, Inc., 2021). However, a Class 2 Cleanroom, which is the second most clean classification there is, must have no more than 4 particles larger than 0.5 microns per cubic meter. Further, a Class 1 Cleanroom cannot have any particles that are larger than 0.3 microns, but may have up to 12 particles per cubic meter that are smaller than that (Clean Air Technology, Inc., 2021).

Cleanrooms are designed for various degrees of air cleanliness based on the requirements of the products in them. The classifications range from ISO 1 to ISO 9, with ISO 1 consisting of the least amount of particles per cubic feet possible, and ISO 9 being equivalent to the average room air quality. In order to achieve these levels of controlled environments, cleanroom designs include air filters, such as a High Efficiency Particulate Air (HEPA) filter, in order to create laminar air flow that can direct air particles downward through the floor to be filtered out. The air distribution system of a cleanroom is critical in maintaining the desired number of particles, but another major factor is the clothing that personnel wear into the clean space. In the highestlevel cleanrooms, you must wear booties, shoe coverts, a full gown, gloves, hairnets, hoods, masks, and eye goggles. However, in a middle range cleanroom, such as an ISO 7, simply booties and a smock may be worn. The material and design of this clothing must be so that it prevents particles from the person to the environment; thus, higher classified cleanrooms have more extensive gowning procedures due to the fact that it must keep the number of particles in the space extremely low (Clean Air Technology, Inc., 2021).

Below is a chart of cleanroom classifications. Headwall Photonics' Cleanroom that this project was involved with is an ISO 7 Cleanroom.



ISO 14644-1 Cleanroom Standards

Class	maximum particles/m^3						FED STD 209E equivalent
	>=0.1 µm	>=0.2 µm	>=0.3 µm	>=0.5 µm	>=1 µm	>=5 µm	
ISO 1	10	2					
ISO 2	100	24	10	4			
ISO 3	1,000	237	102	35	8		Class 1
ISO 4	10,000	2,370	1,020	352	83		Class 10
ISO 5	100,000	23,700	10,200	3,520	832	29	Class 100
ISO 6	1,000,000	237,000	102,000	35,200	8,320	293	Class 1,000
ISO 7				352,000	83,200	2,930	Class 10,000
ISO 8				3,520,000	832,000	29,300	Class 100,000
ISO 9				35,200,000	8,320,000	293,000	Room Air

Figure 3: Cleanroom ISO Classifications (Clean Air Technology, Inc., 2021)

3.9. Chemical Application Techniques

Throughout the process of developing optical gratings, multiple techniques were used to apply different layers to the substrate. The first of these techniques was a spinning technique using a spinning chuck with a removable lid. While the substrate was in the bowl, the chemical layer of photoresist was applied fully across the substrate. The substrate was locked into a circular chuck that spins thousands of rotations per minute. This provided a uniform and micro meter thin coating across the entire surface of the substrate (MicroChemicals, 2021).

Another technique used in the process utilized the evaporation of metals. Metallization occurs during the process to help the reflectivity of the end product. Metal is heated to high temperatures at the base of the coater, and then evaporated onto the substrate surface. This is done using two systems: planetary and stationary (Surtech, 2009).

3.9.1. Stationary Versus Planetary Tooling

The process of depositing metal onto a substrate can be done through either stationary or planetary tools. Stationary tooling allows you to place a substrate on a uniform rack that is held in place while metal is evaporated and deposited onto the surface of the substrate, while planetary tooling spins the substrate so that the metal is deposited evenly. Both of these designs have constraints that must be understood; first, although the planetary tools may result in a more even metallization, it is time consuming to have to secure the substrate into place prior to the spinning, and can further result in defects from the applied pressure. It is simpler to operate with stationary tooling because there is a fixed rack in place that you simply put the substrate on, however it does not produce as uniform results (Bishop & Mount, 2012).

3.10. Evaluating the Quality of the Substrate’s Surface

When evaluating the cleanliness of the substrate surface, for the process of the Headwall’s Gompei Grating, there was less of a concern for small particulates, as this did not negatively affect the part’s effectiveness; however, alteration of the surface tension could result in poor adhesion during the photolithography phase of processing (Armstrong, 2021). Currently, there is no data on the effects of the current acid-based cleaning process to the substrate, other than the fact that the company is experiencing very high scrap rates at the photolithography step. In order to measure the changes in the substrate surface after the pre-clean, the contact angle of the surface could be tested. Although this would not directly be measuring the ‘cleanliness’, it could provide a benchmark as to what the acid wash does to the surface tension of the substrate. This surface tension is important as it facilitates later adhesion with additional layers on the substrate. Through the use of contact angle, the substrate could either be classified as hydrophilic or hydrophobic.

A hydrophobic surface is one that repels water. More specifically, during a contact angle measurement the hydrophobic surface will produce an angle higher than ninety degrees. As the bead of water moves across the hydrophobic surface, it will maintain its shape rather than spreading out (Ibrahim, Nor Azowa, et al, 2019). A hydrophilic surface however, is “water loving” and will spread out across the given surface. This is measured by a contact angle under ninety degrees (Chandler, 2013). Using this contact angle technique, the cleanliness in the surface can be detected by the angle change. If the surface changes from hydrophobic to hydrophilic, it can be predicted that adhesion issues will later occur. Likewise, if the contact angle does not change at all, it could indicate a lack of cleaning.

3.11. Contact Angle Measurement Tool

A contact angle measurement tool, as mentioned in Section 3.7, is used to measure the angle of a surface. It does so by releasing a drop of liquid onto it and measuring the angle of the droplet on the surface through a microscope. The angle obtained from this tool provides valuable information on the surface characteristic, specifically how well a liquid will stick or spread over a surface, which indicates whether it is hydrophobic or hydrophilic. Other applications for contact angle measuring are in the process of evaluating water-proof or water-resistant surfaces, given that you can see how a water droplet interacts with a surface on a very detailed level (Ossila, 2021). For example, the Figure 3 below illustrates the process of using a contact angle measurement tool: approximately 1µL-5µL of any liquid (often pure water) is dropped onto a surface, a bright light is directed onto it from one side, while a microscope is aimed at the droplet from the other side, which displays an image on a computer screen. From this imaging and a contact angle software, a measurement can be taken as shown below.

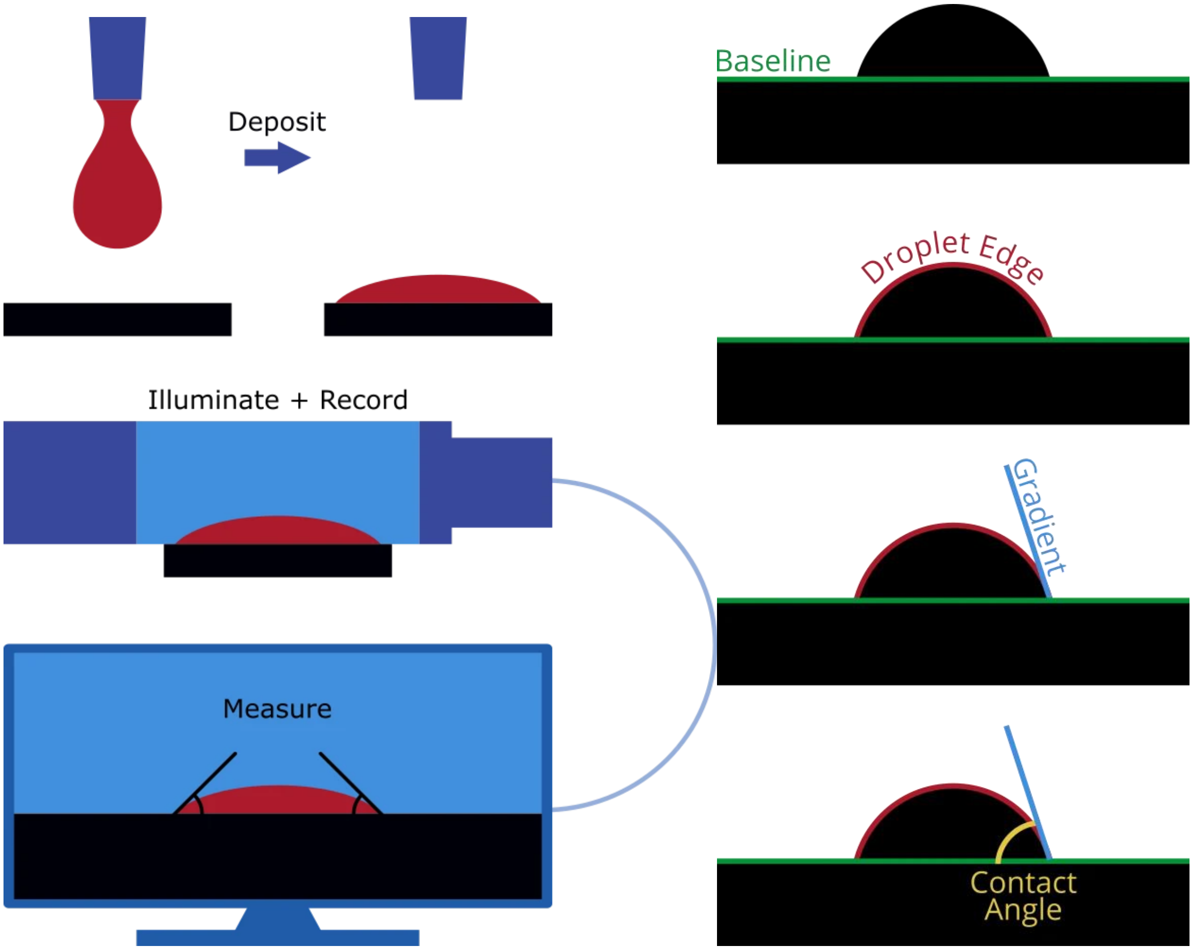


Figure 4: Contact Angle Measurement Process (Ossila, 2021)

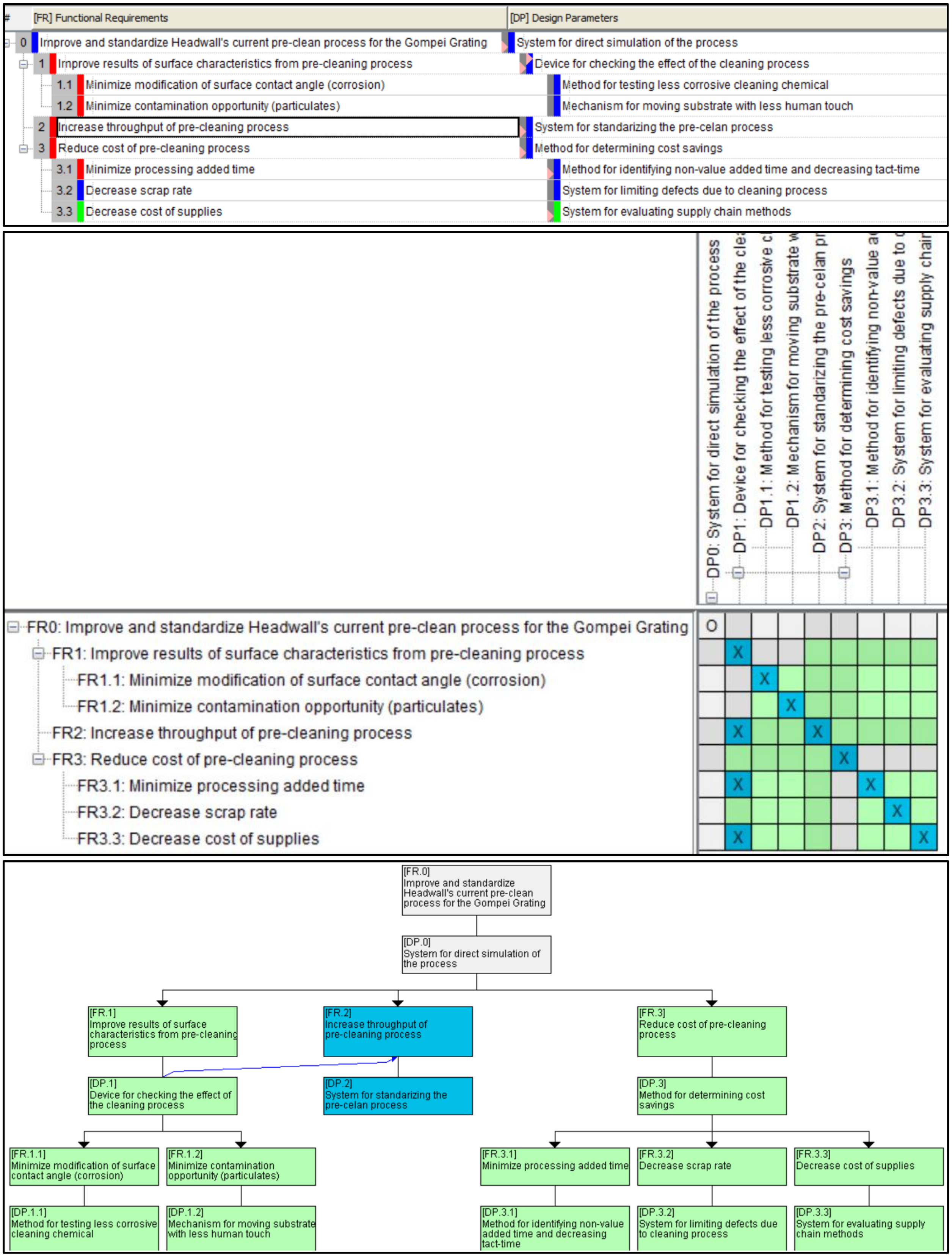
3.12. Plasma Institute at Drexel University

Our team had the opportunity to speak with Alexander Fridman, a leader in the Plasma Chemistry and technology field. Alexander Fridman, the current Director of the C.J. Nyheim Plasma Institute at the Drexel University College of Engineering, “is a recognized world leader in research relating to plasma science and engineering… renowned for his developments in novel plasma approaches to material treatment, fuel conversion, hydrogen production, aerospace engineering, biology, environmental control, agriculture and food processing" ("Alexander Fridman and the Nyheim Plasma Institute of Drexel University", 2020). The Nyheim Plasma Institute is also the "birthplace of the field of plasma medicine, with a commitment to its educational mission and to creating a collegial research environment supporting breakthroughs in plasma science and engineering" ("Alexander Fridman and the Nyheim Plasma Institute of Drexel University", 2020). Through a connection with Professor Guceri, we spoke to Fridman about how the plasma could help Headwall with their cleaning process of the substrates created.

4. Methods

4.1. Axiomatic Design

We decided to create axiomatic design decomposition for the pre-clean process at Headwall. We started by first identifying the top and upper-level functional requirements for the process. After choosing broad functional requirements, we figured out other functional requirements that would fall into those brackets. We then connected each functional requirement with a design parameter. In AD, it is essential to find the relationships between the functional requirements and the design parameters. Although when you think about AD it is important to think about all relationships, you only need to mark the relationships that have a negative impact on one another. Any positive or neutral relationships you will not look into changing, so you do not need to mark an x for those sections. In the chart below, the negative relationships are identified with FR 2, 3.1, 3.3, and DP 1.



#	[FR] Functional Requirements	[DP] Design Parameters
0	Improve and standardize Headwall's current pre-clean process for the Gompei Grating	System for direct simulation of the process
1	Improve results of surface characteristics from pre-cleaning process	Device for checking the effect of the cleaning process
1.1	Minimize modification of surface contact angle (corrosion)	Method for testing less corrosive cleaning chemical
1.2	Minimize contamination opportunity (particulates)	Mechanism for moving substrate with less human touch
2	Increase throughput of pre-cleaning process	System for standarizing the pre-celan process
3	Reduce cost of pre-cleaning process	Method for determining cost savings
3.1	Minimize processing added time	Method for identifying non-value added time and decreasing tact-time
3.2	Decrease scrap rate	System for limiting defects due to cleaning process
3.3	Decrease cost of supplies	System for evaluating supply chain methods

	DP0: System for direct simulation of the process	DP1: Device for checking the effect of the cle	DP1.1: Method for testing less corrosive c	DP1.2: Mechanism for moving substrate w	DP2: System for standarizing the pre-celan pr	DP3: Method for determining cost savings	DP3.1: Method for identifying non-value a	DP3.2: System for limiting defects due to c	DP3.3: System for evaluating supply chai
FR0: Improve and standardize Headwall's current pre-clean process for the Gompei Grating	O								
FR1: Improve results of surface characteristics from pre-cleaning process		X							
FR1.1: Minimize modification of surface contact angle (corrosion)			X						
FR1.2: Minimize contamination opportunity (particulates)				X					
FR2: Increase throughput of pre-cleaning process		X			X				
FR3: Reduce cost of pre-cleaning process						X			
FR3.1: Minimize processing added time		X					X		
FR3.2: Decrease scrap rate								X	
FR3.3: Decrease cost of supplies		X							X

[FR.0] Improve and standardize Headwall's current pre-clean process for the Gompei Grating

[DP.0] System for direct simulation of the process

[FR.1] Improve results of surface characteristics from pre-cleaning process

[FR.2] Increase throughput of pre-cleaning process

[FR.3] Reduce cost of pre-cleaning process

[DP.1] Device for checking the effect of the cleaning process

[DP.2] System for standarizing the pre-celan process

[DP.3] Method for determining cost savings

[FR.1.1] Minimize modification of surface contact angle (corrosion)

[FR.1.2] Minimize contamination opportunity (particulates)

[FR.3.1] Minimize processing added time

[FR.3.2] Decrease scrap rate

[FR.3.3] Decrease cost of supplies

[DP.1.1] Method for testing less corrosive cleaning chemical

[DP.1.2] Mechanism for moving substrate with less human touch

[DP.3.1] Method for identifying non-value added time and decreasing tact-time

[DP.3.2] System for limiting defects due to cleaning process

[DP.3.3] System for evaluating supply chain methods

Figure 5: Axiomatic Design of Pre-Clean Process

4.2. Value stream mapping

Headwall also asked our team to focus specifically on the pre-clean section of their manufacturing process for the Gompei Grating. In order to determine areas that required improvement, we first needed to fully understand the entire process of the part - from obtaining supplies, to processing, and packaging. Below is a flow diagram developed to illustrate the Gompei Grating’s process from start to finish. Another diagram was further developed, highlighting the details of the pre-clean step of the process, which is shown in Figure 7.

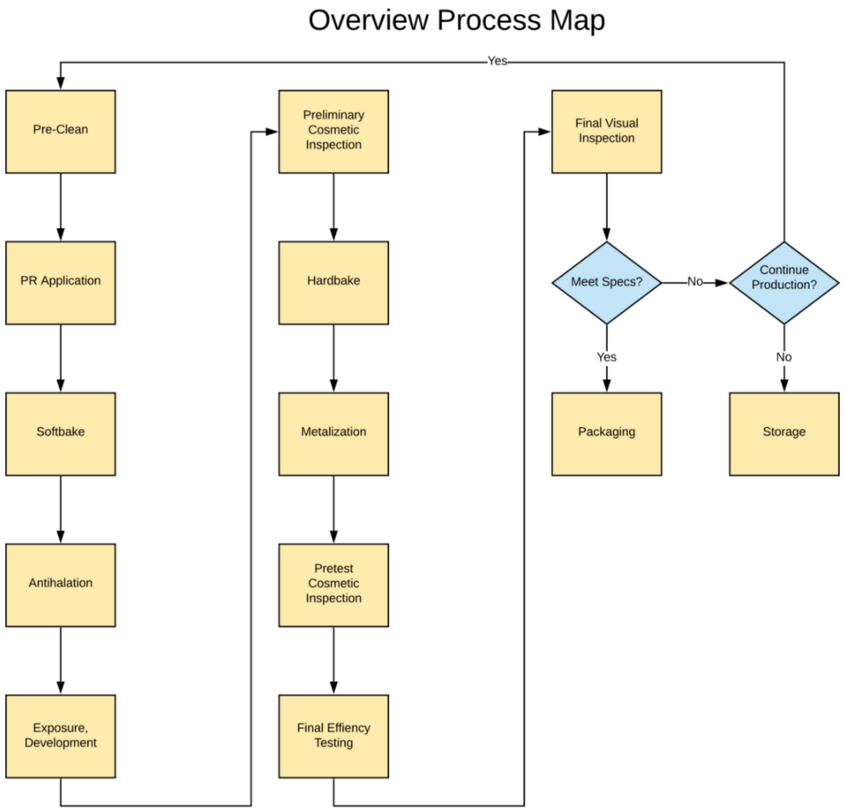


Figure 6: Overview Process Map

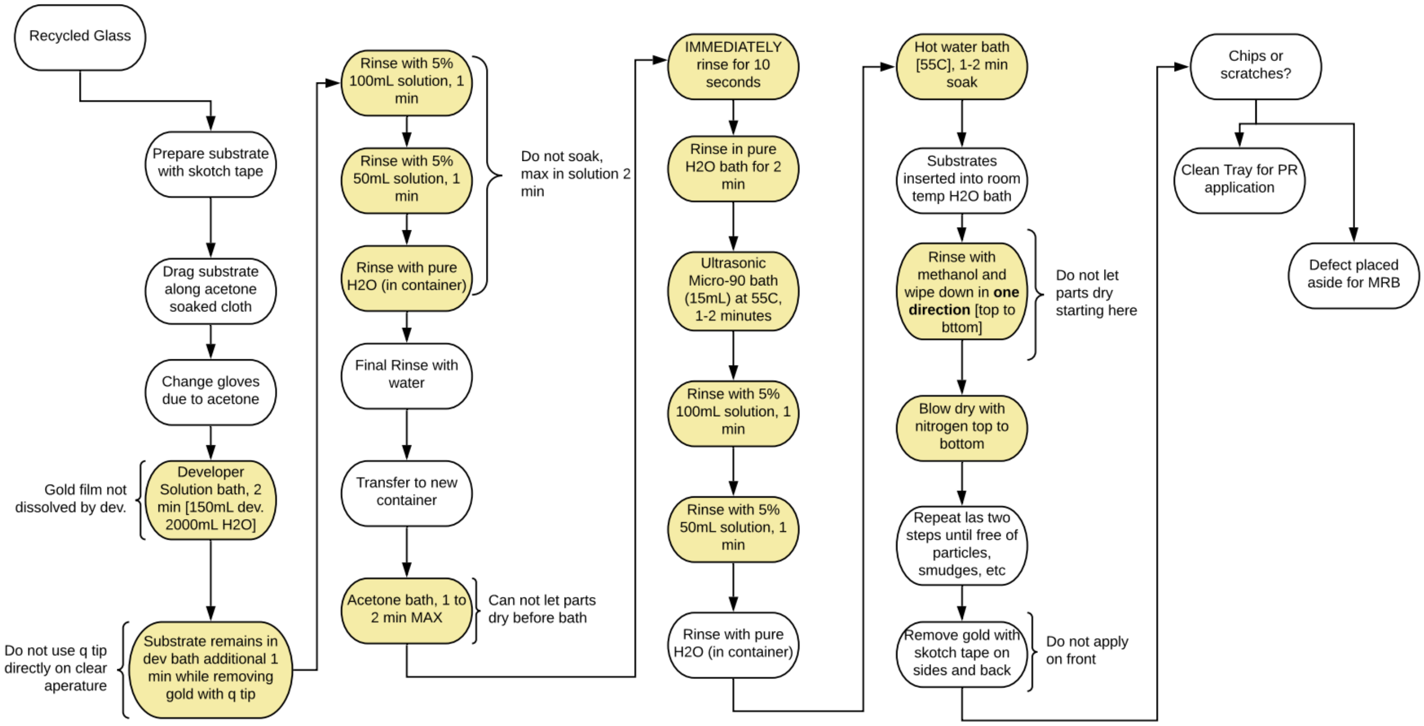


Figure 7: Pre-Clean Process Map

From these process maps, we created a value stream map in order to identify wastes, and improve Headwall's pre-clean process. This later enabled us to display the recommendations we had in making it a stronger process. Figure 8 below shows our initial value stream map based on information gathered through discussions with Headwall.

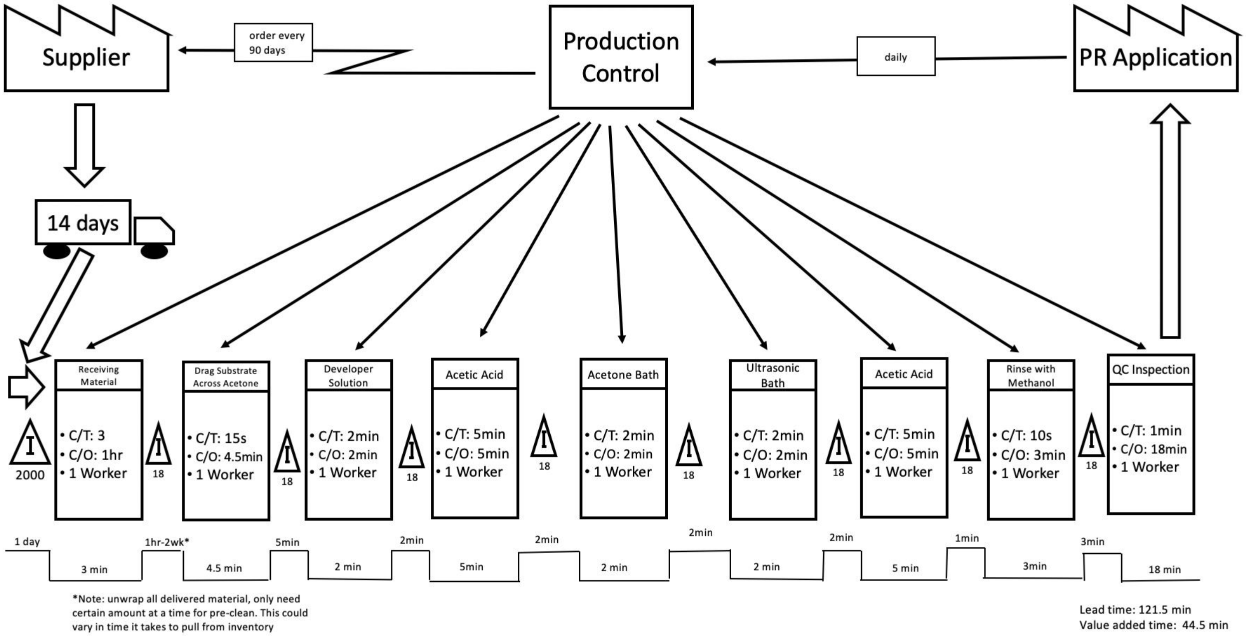


Figure 8: Predicted Value Stream Map

4.3. Lean Manufacturing

4.3.1. Seven Wastes of Manufacturing

Developed by Taiichi Ohno, for the improvement of Toyota's production system, the seven wastes (Muda) of manufacturing were inspired by the United States movement of lean manufacturing (Shamni, 2009). The seven wastes of manufacturing are transportation, inventory, motion, waiting, overprocessing, overproduction, and defects. All seven wastes are not prominent in every scenario, and for this project we focused on the waste that comes from defects, overprocessing, waiting, inventory, and transportation in the Headwall process. Defects were used to look at the poor yield because most of the developed glass has to be scraped and re-sent through the entire process which is wasting time for Headwall. Our team looked at how overprocessing can be improved by standardizing the processes at Headwall. For waiting we identified how to eliminate dwell time for Headwall. Our team decided to implement a pull system at Headwall to assist in recognizing when to purchase products to have a steady inventory level. Through creating more efficient packaging procedures at Headwall, we hoped to reduce transportation.

4.3.2. Pull System

Headwall Photonics could have benefitted from a pull system due to their difficulties in inventory forecasting. Having a pull system enables the individual in charge of ordering parts to organize the inventory and identify what is needed at certain parts of the year depending on customer demand. A pull system enables parts of the company to be automated or have a Kanban system. This reduces the number of instructions the employees need to process in work orders or emails when ordering new parts. The main aspect is identifying when the parts are empty, so the pull system automatically orders new parts that would be ready for the next process that needs to be completed. A pull system would help to reduce inventory at Headwall.

After researching a variety of pull systems, we determined that constant work in progress (CONWIP) would be the best option for Headwall to use. The common pull system to use is a Kanban system which labels part numbers, but it works best with “high-volume, low-mix production” (Roser et al., 2020). CONWIP works by not having a specific card associated with a type of part making it ideal for “Low-volume, high-mix product” (Roser et al., 2020). In CONWIP “when a part is removed from the CONWIP inventory, the CONWIP card is blanked… when a CONWIP card comes back, it merely has the information to produce whatever job is next in line” because the card is not specifically associated with a part (Roser et al., 2020). When using a CONWIP system, the company needs to have “a backlog list of open jobs to be completed” (Roser et al., 2020). Since the next jobs should be organized by how soon they are needed, this also enables a company to improve at prioritizing tasks.

Based on the inventory count we assisted Headwall to complete, implementing a CONWIP system is a beneficial way to have better organization of inventory and stronger inventory forecasts. This limits the amount of inventory Headwall is ordering at a time which will also lower company costs by reducing inventory on hand.

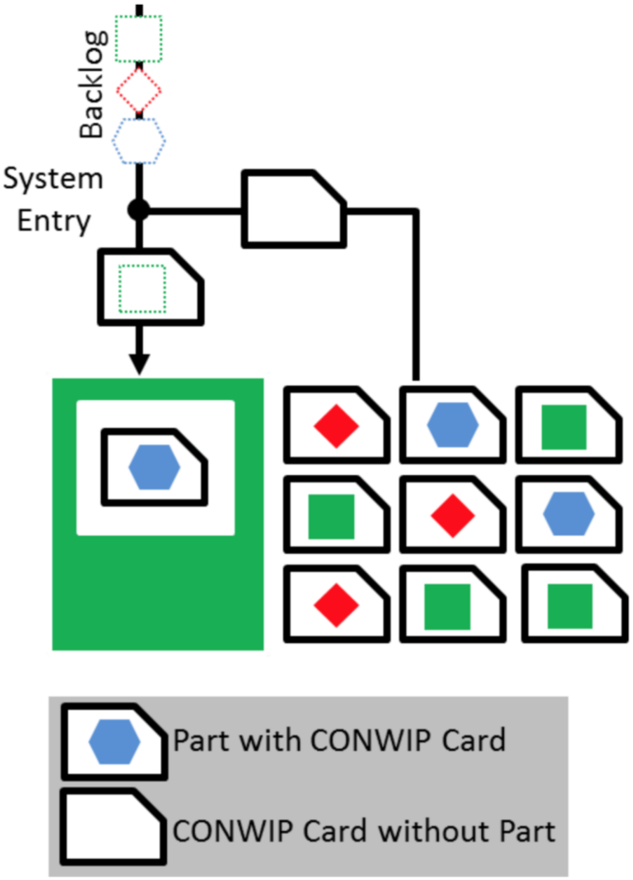


Figure 9: CONWIP Diagram

4.3.3. Data Driven Decision Making

Gage repeatability and reusability (Gage R&R) for the Gompei Grating process can present significant savings in rework costs for Headwall Photonics as it displays "the amount of variation in the measurement system" (Gage R&R, 2021). Specifically, being able to identify standard parameters from the contact angle measurement tool that can be used after the pre-clean operation in the manufacturing process.

Developing a spectrum of standards that met the tolerance standards for Headwall required a variety of data that to be analyzed and run through the process to determine the contact angle spectrum that meets company standards. This data then was used to design parameter values as well as design corrective actions from trend data. For example, if substrates going through the pre-clean process are beginning to breach standards, corrective actions that have been identified from the analysis can mitigate rework in the pre-clean process. Overall, this process required a wide array of data that goes through the system and can be analyzed to identify standards and design corrective actions from trends.

4.3.4. Standardization for Efficiency

In order to understand the best way to standardize a traveler for Headwall, our team decided to look at the traveler like an outsider seeing it for the first time. This enabled us to evaluate the simplicity of the traveler and what parts of it needed to be changed. We looked at what should be deleted or just altered to be clearer to someone that is new to the process, such as an operator seeing it for the first time. Our team also considered the parameters that were required on the traveler and the possibility of making the process for filling out the traveler digital.

4.4. Direct Simulation of Process

4.4.1. Setting up the process

In order to gauge the variability from person to person, as well as conduct testing between various cleaning baths, the same materials used at Headwall were gathered. Headwall provided acetone, methanol, bins, baskets, and sample substrates to conduct a mock Gompei Grating production process. A diagram of the process set up can be seen in Appendix B. Although this was not performed in a clean room, the main focus of the mock process was to evaluate the surface chemistry of the substrate after cleaning. For this reason, basic equipment such as heated baths were used, but nothing to simulate a clean room environment as it was deemed not necessary.

4.4.2. Conducting the process

In order to achieve a similar acid bath process to Headwall, the same procedure and chemical ratios were executed. Although different operators (each team member) conducted the process, the same work instructions were followed. The acetic acid process was conducted as follows:

Step	**Description**
1	Set up three bins, with varying amounts of acetic acid, as seen in Figure 10. ● First bath contained 100mL of acetic acid, followed by 50mL of acid, and then finally a pure water rinse
2	An ultrasonic bath was filled with acetone and heated
3	One substrate was placed in the metal basket, which was then placed in the first bath for approximately 1 minute
4	The metal basket and substrate were then quickly transfer to the second bath and let to sit for 1 minute
5	The metal basket and substrate were then quickly transfer to the third bath and let to sit for 1 minute
6	The metal basket and substrate were then quickly transferred to the ultrasonic bath for 2 minutes
7	The metal basket and substrate were removed from the ultrasonic bath and steps 3 through 5 were repeated
8	The substrate was then removed from the last bath and taken out of the metal basket using gloves and only touching the outside edges
9	The substrate was rinsed with acetone
10	The substrate was dried using pressurized nitrogen
11	The substrate was re-wrapped in original packaging

After the process was completed, the surface contact angle was tested and compared to that of the original substrate. This gave an indication of the success of the process. While performing all experiments, acetone and methanol were used. In order to safely handle these chemicals, gloves and safety glasses were worn at all times. All precautions given on the chemical fact sheets were followed.

Figure 10: Direct Simulation of the Process

4.5. Contact Angle Measurement Tool

After the pre-clean process was conducted, the corresponding substrates that go through pre-clean were measured using a Contact Angle Measurement Tool. This instrument was located on WPI's campus in Goddard Lab 004. This instrument will help our group determine the effects of different cleaning chemicals on the substrates and further help us to improve and standardize the process. Using water, this instrument measures the contact angle on ends of the substrate and allows us to analyze changes in the pre-clean process, as described in Section 3.9. This instrument releases a drop of water on the top of the substrate (flat side facing up), and using a projection camera, the angle between the ends of the substrate and the drop can be determined to understand the specific angle of the substrate; this setup can be seen in Figure 11. We utilized this to collect measurements of surface angles of base substrates before pre-clean, all of the substrates we tested in acetic acid baths, and also an equal number of substrates that were processed using CO_2 instead of acetic acid. An example of what was observed through the contact angle software is shown in Figure 12, which is the camera image of the water droplet on the surface, along with the measured angles. For each substrate being tested, we tested three droplets - for every droplet we collected three angle measurements immediately, then waited ten seconds and recorded three more angles, and finally repeated one last time to evaluate how fast the water spreads on the surface. This process is outlined below.

Steps	**Description**
1	Place substrate on platform with the flat side facing up
2	Adjust the position of the dropper and camera angle to give you the proper image window, as seen in Figure 12
3	Press “Drop” on the user interface to release a droplet of water
4	Press “Start” and then press “Measure” 3 times in a row (<1s apart) to record 3 immediate measurements of the contact angle
5	Press “Stop” and wait 10 seconds to allow water droplet to spread ● Have partner record the average of the first 3 measurements
6	Repeat Steps 4 and 5 to obtain an average measurement for the contact angle after 10 seconds
7	Repeat Steps 4 and 5 to obtain an average measurement for the contact angle after 20 seconds
8	Rotate the substrate and align the dropper to dispense a new drop on a clear area
9	Repeat Steps 4-7 to obtain measurements for the **2nd** drop on this substrate
10	Rotate the substrate and align the dropper to dispense a new drop on a clear area
11	Repeat Steps 4-7 to obtain measurements for the **3rd** drop on this substrate
12	Remove substrate and place the next substrate on the platform
13	Repeat Steps 1-13 for until all substrates have been processed ● Refill water supplying the tube when the use interface shows it is low, or it is noticed that full droplets are not dispensing

. The average measurements of these substrates contact angles were analyzed and compared to determine if chemical baths negatively affect the surface tension. We would like to thank Professor Lambert and graduate student Ziyang Zhang for allowing us access to this equipment and teaching us to properly operate the instrument.

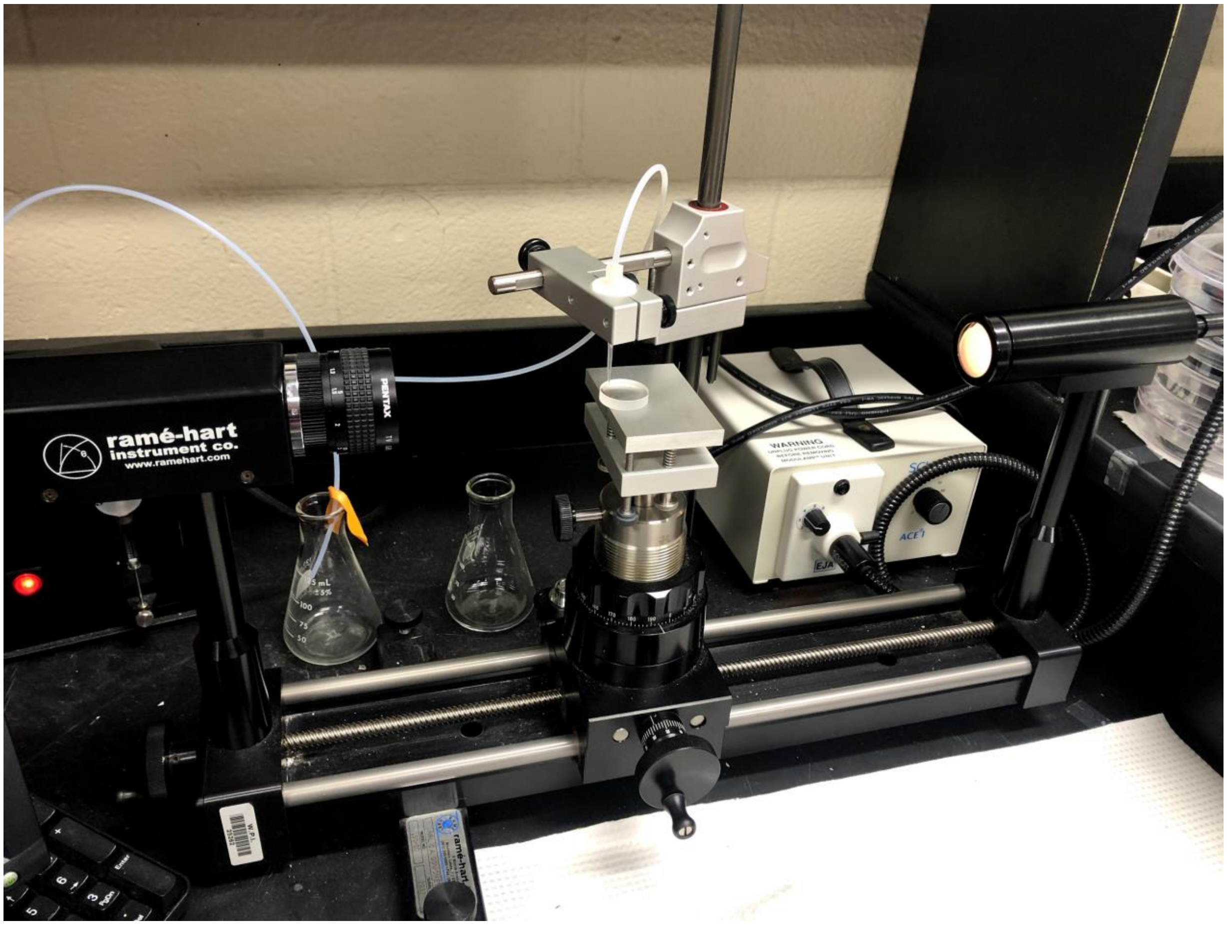
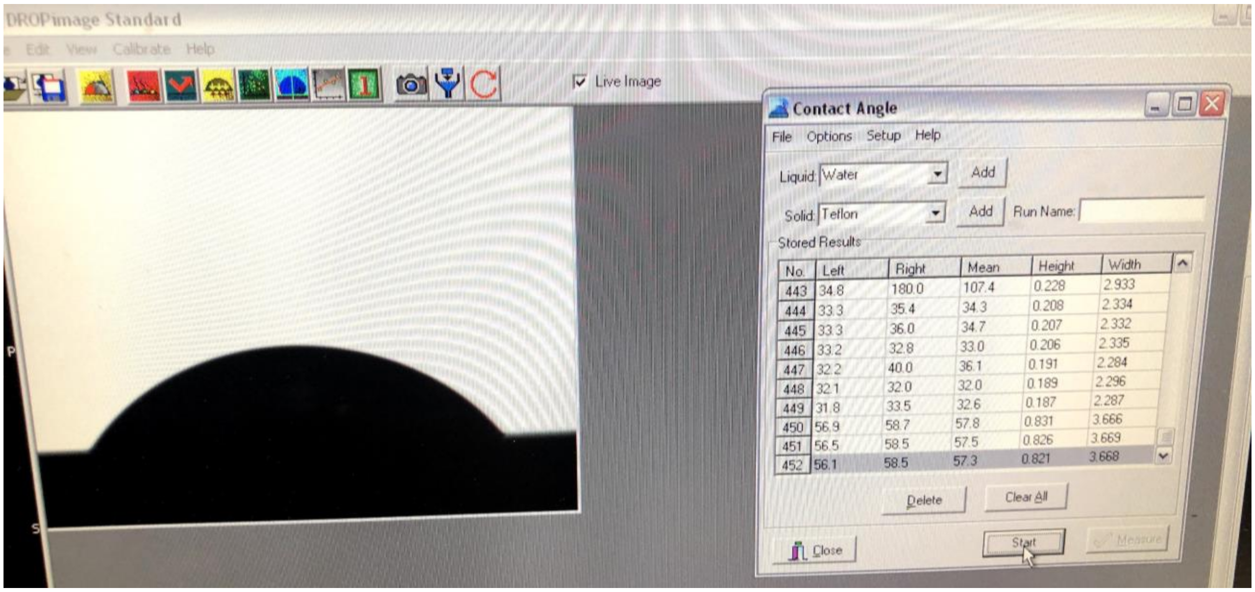


Figure 11: Contact Angle Measurement Tool Setup



Liquid: Water

Solid: Teflon

Run Name:

Stored Results

No.	Left	Right	Mean	Height	Width
443	34.8	180.0	107.4	0.228	2.933
444	33.3	35.4	34.3	0.208	2.334
445	33.3	36.0	34.7	0.207	2.332
446	33.2	32.8	33.0	0.206	2.335
447	32.2	40.0	36.1	0.191	2.284
448	32.1	32.0	32.0	0.189	2.296
449	31.8	33.5	32.6	0.187	2.287
450	56.9	58.7	57.8	0.831	3.666
451	56.5	58.5	57.5	0.826	3.669
452	56.1	58.5	57.3	0.821	3.668

Figure 12: Contact Angle Measurement Data Example

4.6. Cost-Benefit Analysis

Once identified value added changes were confirmed, an effective cost-benefit analysis of the changes was observed and presented to management at Headwall. The purpose of this process is to include quantified savings of changes to the process and provide a metric to understand why a change has to be made. This analysis included a multitude of quantities, but most likely will use evidence metrics such as improved scrap rate, decreased process time, Muda waste calculation, and also included training materials that will cover training sessions to certify employees of the new process. The purpose of these training sessions was to ensure effective standardization of the modified process to ensure quantified metric savings can and will be met. The implementation of a pull system assisted with the costs of this process. Less inventory will need to be kept in the company which lowered the holding costs and ordering costs will be lowered with an organized inventory system such as the CONWIP system we recommended.

4.7. Use of Plasma Application for Pre-clean

The application of plasma in removing microbes and small particles present on surfaces is applicable to the pre-clean process of substrates at Headwall. The Plasma Institute at Drexel University run by Alexander Fridman investigates the application of plasma for certain applications in the industry as well as scientific research. A sample of substrates were sent to the Institute to investigate the use of plasma cleaning to correspond to an effective contact angle of the substrate.

If this process presents feasible results, the next step will be to investigate incorporating plasma cleaning in the pre-clean process for Headwall. This process involved a cost-benefit analysis of the change in cleaning methods as well as feasibility of incorporating the same tooling at Headwall.

4.8. Prototyping and Iterations

One of our goals was to redesign a testing fixture for Headwall that would help improve the efficiency and yield of this process, that is separate from the Gompei Grating process described above, but it is a major challenge for them at the moment. Currently, it takes too long to carefully load and unload substrates in the fixture and it is also easy to accidentally damage a substrate as you try to load it in.

The process we took to approach this problem was to evaluate their fixture, given that Headwall was able to ship us the physical fixture so we could take a closer look. We then brainstormed a more efficient and simple design, making a CAD model of it based on the required dimensions provided to us, as well as the desired functionality. The goal was to easily load and unload and minimal room for damaging the part. From here, we developed prototypes and went through multiple design iterations in order to find an optimal solution.

4.8.1. First Iteration

The first option we explored was using springs to lock the substrate into place and then release it with the push of a button or switch, so that an operator would not have to physically adjust the fixture to load or unload the substrate. Although this allows for a smooth and easy loading of the substrate into place, we determined that the spring force would be too strong and could lead to damages to the substrate as it propels it out of the fixture. Damages could occur from either rattling against the sides of the fixture, or being propelled all the way out and landing on the table. This led us to search for a more controlled method of removing the substrate.

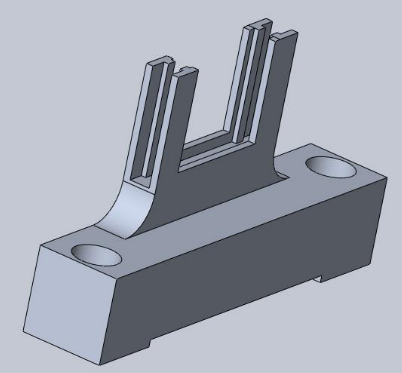


Figure 13: First Iteration Fixture Mount Prototype

4.8.2. Second Iteration

Our next proposed design was a gear system because it would be more controlled than the springs. We designed and 3D printed a small-scale CNC gear system, however it proved difficult to get them working at the small size that was needed to fit inside the fixture dimensions. The motor also proved difficult to fit inside the small-scale fixture.

4.8.3. Third Iteration

This led us to explore the option of a linear actuator, given it is simple, controlled, and automatic which limits human touch and room for error. After thorough research into purchasing a linear actuator to incorporate into our design, we determined that we would need to build one in order to fit our dimensions. However, due to complication of building this from scratch and the limited timeline we were operating on, we decided to circle back to the spring concepts and explore this possibility further.

A small spring, similar to that of what is in a pen, along with an adjusted model, served to be the successful design to address the problems Headwall faced with their current fixture. We designed the new fixture to have slots that fit these small springs in the rails and used a low spring force and a locking/releasing mechanism to create a more controlled process.

5. Results

5.1. Axiomatic Design Decomposition

Through completing the AD, our team was able to help Headwall move away from having unpredictable iterations in the pre-clean process. The results of the AD decomposition showed that we could identify whether the sub goals could be accomplished independently or not and that the pre-clean process has to be completed in a certain order. The coupling matrix specifically showed that if you do not accomplish the cleaning steps in the specific order specified, it would have to be redone. This is an over processing waste for the company and likely wastes both time and materials and falls into the seven wastes of manufacturing. AD helps to explicitly define what happens, so over processing does not occur. If over processing occurs and the pre-clean problem goes all the way to the manufacturing team, this will be more materials and time wasted as the pieces will then have to be disposed of or brought back to the first part of the pre-clean process. This all depends on the adjustment of the system.

5.2. Value Stream Mapping

After evaluating the processes at Headwall Photonics, Figure 14 shows a more accurate value stream map that we were able to develop after more in depth analysis and discussions with various supply chain, manufacturing, and engineering employees at Headwall.

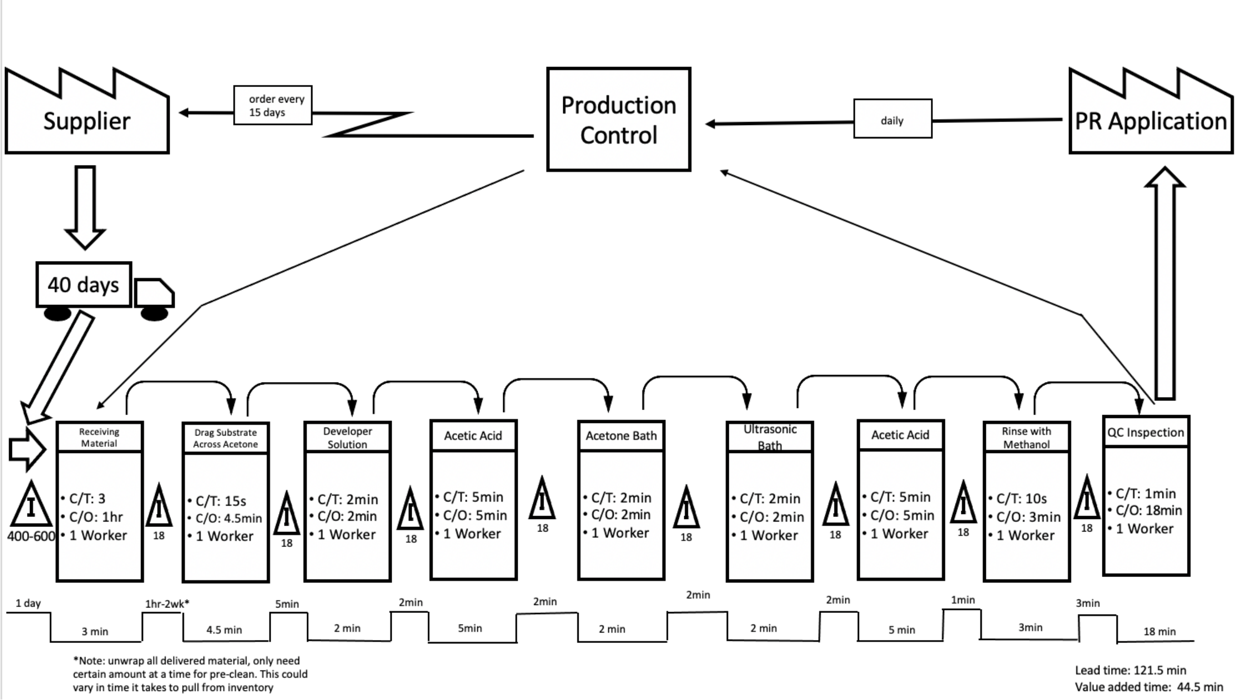


Figure 14: Accurate Value Stream Map

5.3. Lean Manufacturing

5.3.1. Seven Wastes of Manufacturing

One way waste could be reduced at Headwall is through the implementation of the pull system our team is recommending. The pull system would mean that less inventory is sitting at Headwall which would lower the holding costs. Implementing the pull system would also make it easy to identify what inventory is needed and what can be eliminated. Another way waste was reduced was standardizing the pre-clean process at Headwall. After having each person on our team perform the process, we were able to determine what steps should be eliminated from the process sheet and what steps should be added. Having too many directions that flood the process is an example of overprocessing because there is no need to read those instructions if they will not actually help the process move along.

5.3.2. Pull System

The goal of implementing a pull system at Headwall Photonics was to have an inventory forecasting system for the company to use for products. Our team suggested a CONWIP system to do on a trial basis and see the impact it had on Headwall. Due to COVID-19, we could not be at Headwall Photonics to help implement a pull system, but we have suggested they follow CONWIP as it is a lean pull system and has potential to assist them in forecasting effectively for future products. At this point we have not received any results on the impact of the implementation.

5.3.3. Gage R&R

Gaging Repeatability and Reproducibility of substrates in the pre-clean process empowers data to drive standard move procedures, company manufacturing parameters, and mitigates waste in the process by using data to drive business decisions. Gage R&R synthesizes statistical process control to develop a set of standards that can be applied for substrate parameters of their contact angle (a range of values that are compliant with the rest of the process) that simplify the inspection process throughout production of substrates. This kind of data driven decision making can be applied at Headwall Photonics.

The experiment conducted in our study was the collection of a repeatable process in the pre-clean operation by multiple stakeholders through multiple trials. From this point, the measured contact angles of these substrates (that are compliant) can prove to be set parameters to meet in the pre-clean process. This kind of sampling requires an initial investigation of these substrates to determine initial parameters with short-term sampling as well to ensure customer specifications are met as well as limit recycling of the substrates. Once these initial standards are in place as well as routine tests, it is possible to go further and identify parameters to have corresponding corrective actions if they meet at a certain level. These will assist in the design of standard move rules in the process and will help mitigate the waste of both workforce capital and recycling of substrates in the process.

5.3.4. Standardization for Efficiency

Based on our analysis of the pre-clean process we have decided the process, and instructions need to be standardized. As pictured in Figure 7 earlier in the paper, the current process map for pre-clean that Headwall references has 26 steps. Headwall does not use all of these steps therefore their process map is inaccurate. Because of this, Headwall is seeing tribal knowledge currently. The processes are being taught by word of mouth and being passed along to new employees. This does work for Headwall currently because the team is small but for true process improvement, the process should be well defined and completely standardized. Our team created a new process map to display the current pre-clean process accurately. Along with this, we created a detailed written instruction sheet for any new employee to follow. To ensure anyone could do the pre-clean process with no direction we have created a picture to show the setup of the process as well. With these three deliverables, Headwall will be following a standardized process. See Appendix A for the standardization documents.

5.4. Physical Simulation of Pre-clean Process

Although we were able to run the process, there were obstacles that occurred along the way. The first challenge had to do with getting supplies; since we were trying to replicate the process Headwall had as close as possible, we had to rely on them shipping us necessary equipment and chemicals, however, it took trial and error to figure out exactly what was needed and wait for them to get approval to send us items. Additionally, we attempted to find access to certain chemicals and equipment at WPI, but under pandemic circumstances, and the unique process we were looking to simulate, this proved to be a long process. Space on campus was limited, but we were able to find somewhere to store supplies for our process and a room to complete the process in, both in Higgins Labs. Another aspect that was difficult to control in the physical process was that we used the same bins each time someone in our team performed the process. During the process we coated the glass in methanol and back in the pure water. This made the pure water have methanol in it for the next participant performing the process making it a different process for the glass after that. The water that was used in the baths was around three liters, but not exact. This means that the acetone baths had a different proportion of acetone in it every time we performed the process.

As mentioned previously, our team simulated the process at WPI where we recreated the pre-clean room set up. We then used Headwall's prepared process map to guide us through the process. As we worked through the process, we found that we relied on our team member, Kaitlyn's, help, who was familiar with the process from an internship with Headwall over the summer. We recognized this as an issue, given that it indicated that operators at Headwall also likely perform this process based on tribal knowledge, rather than the process sheet or work instructions. This resulted in our team believing that a new process map would be helpful to Headwall and would clarify the process therefore reducing any variability. Figure 15 shows the new process map for the pre-clean process based on the necessary steps that are actually conducted.

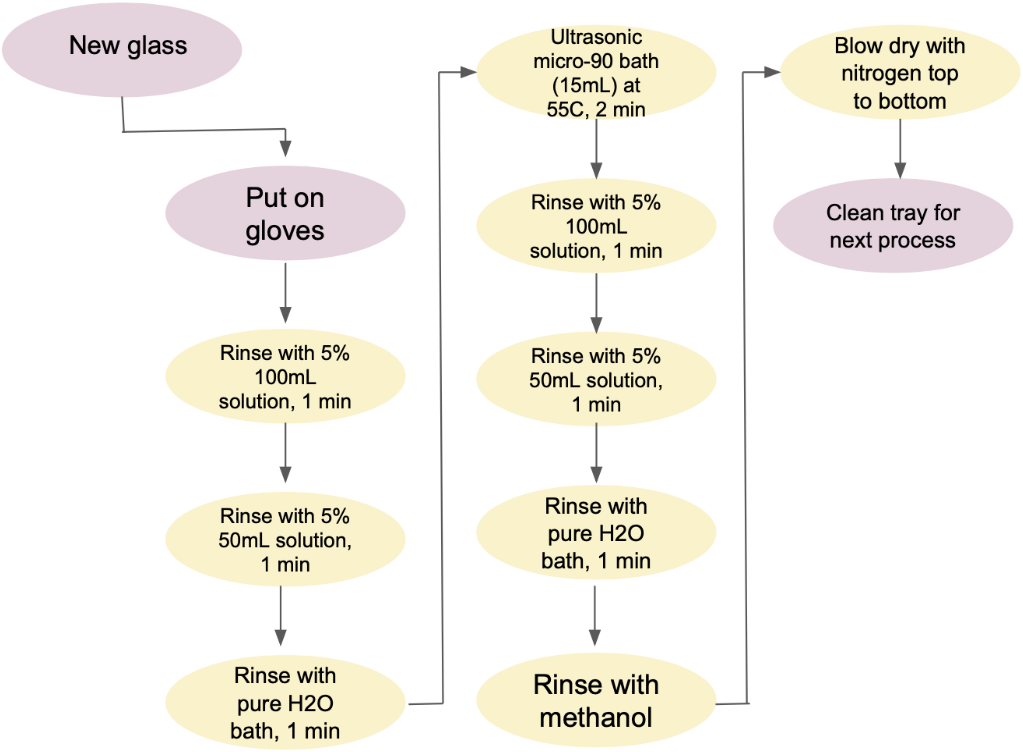


Figure 15: Newly Developed Pre-Clean Process

Despite the above challenges, we were still able to successfully run ten substrates through the acetic acid pre-clean process. Each member of our team ran two substrates each, putting both through the process simultaneously, similar to how Headwall performs this process in batches. The time was recorded for each person from the start of the first bath, to when they finished drying the last substrate; the results of this time trial can be seen in Table 1 below.

Table 1: Time Trials for Pre-Clean Process

	Total Time	mm:ss	minutes	Variation (mm:ss)
Kaitlyn	11m 10s	11:10	11.17	0:13
Caitlin	11m 43s	11:43	11.72	0:46
Johann	10m 34s	10:34	10.57	0:22
Kayla	10m 7s	10:07	10.12	0:49
Carson	11m 7s	11:07	11.12	0:10
Average	10m 56s	10:56	10.94	
Standard Deviation			0.61	
Average Deviation (Variation)			0.48	

The average time taken to complete the pre-clean process was 10 minutes 54 seconds, however, this includes one person taking 11 minutes 43 seconds while another completed the process in only 10 minutes 7 seconds. This variation could be attributed to how long it took each individual to lift the basket holding the substrates out of one bath and into the next - although this is a minor variation, the transfer between baths occurs six times throughout the pre-clean process so this could add up and result in varying total process times. Additionally, since each bath was timed using an hourglass timer, one operator may have taken longer than another to start the timer after placing the basket in the baths, or on the other hand, could have taken a fraction of moment longer to remove the basket once time ran out - again, since these bath transfers occur six times, minor differences add up to result in significant variations, as seen below.

5.5. Contact Angle

The results of the contact angle measurements taken provided data on the both the acetic acid bath process and the CO_2 cleaning process. Further, a correlation presented itself between how long the operator took to complete the pre-clean process, and the corresponding contact angle of the surface. Table 2 below outlines the data collected from the contact angle measurement tool. Each person's two samples were average together and compared to the other members' angle results. With this, we are able to analyze not only the difference between contact angle measurement of the substrate before and after processing, but also how these angles vary from operator to operator. The “Average of Processed (Drop 1)” column shows the contact angle of the first drop placed on the processed sample, measured immediately. The column to its right shows the angle of the same drop on the same sample, after 10 seconds elapsed; the third column, similarly, after 20 seconds passed). The column titled “Average of Processed (Drop 2) shows the angle measurement taken immediately after dropping a second drop of water on the same processed sample, followed by measurements taken after 10 and 20 seconds respectively. As mentioned previously, each person ran two samples, so these measurements are the average of each person’s two samples. Finally, the bottom row highlights the total average of all ten samples contact angle measurements over 10 second intervals.

Table 2: Contact Angle Measurements - Acetic Acid Samples

Person	AVERAGE of Processed (drop 1)	AVERAGE of Proc (after 10s)	AVERAGE of Proc (after 20s)	AVERAGE of Processed (drop 2)	AVERAGE of Proc (after 10s)	AVERAGE of Proc (after 20s)
Caitlin	**47.425**	46.775	46.175	**48.725**	48	47.55
Carson	**52.175**	51.475	50.775	**55**	54.125	53.575
Johann	**55.175**	54.4	53.75	**50.875**	49.925	49.1
Kaitlyn	**54.3**	53.125	52.6	**57.625**	56.875	56.25
Kayla	**60.35**	59.475	57.85	**59.65**	58.9	58.225
Averages	**53.885**	**53.05**	**52.23**	**54.375**	**53.565**	**52.94**

In order to compare the acetic acid process to CO_2, we needed to compare their contact angle measurements after processing. Therefore, we collected ten samples from Headwall that had been cleaned using CO_2 instead of the acetic acid baths for use to measure. Our team brought these samples to the lab and measured the surfaces' contact angles in an identical way as we did for the acetic acid samples - we measured 2 drops per sample and collected three measurements per drop, over 10 second intervals. In an attempt to limit variability and enhance the reliability of our results, we had the same person operate the tool, the same person record measurements, and the same person timing as we did prior. The results of this are outlined in the table below. The main difference is that Headwall had two operators perform the process on five samples each, rather than five different people; however, the averages over all ten samples are still comparable.

Table 3: Contact Angle Measurements – CO_2 Samples

Person	AVERAGE of Processed (drop 1)	AVERAGE of Proc (after 10s)	AVERAGE of Proc (after 20s)	AVERAGE of Processed (drop 2)	AVERAGE of Proc (after 10s)	AVERAGE of Proc (after 20s)
A	**52.57**	46.55	45.1	**53.38**	48.4	46.96
B	**55.9**	49.41	47.02	**59.4**	52.51	50.11
Averages	**54.24**	**47.98**	**46.06**	**56.39**	**50.46**	**48.54**

As can be seen through this data, the initial contact angle of each drop, right after landing on the surface, are similar in both sets of samples; however, the angles declined much more after ten and twenty seconds for the CO_2 samples, as compared to the acetic acid samples. Conclusions that we can draw from these results are described in detail in the following section.

5.6. Cost-Benefit Analysis

Through access to a contact angle measurement tool at WPI, we were able to not only simulate Headwall's processes, but also test the results by comparing surface tension measurements. This is a step that Headwall periodically does by shipping random samples to California to have tested on a Contact Angle Measurement tool.

Although this tool did help us to experiment with variations to the process and analyze which were most effective, we do not see it is a necessity that Headwall invests in purchasing this tool themselves, which was one of the originally posed questions to use from the company. We came to this decision based on our results from the process analysis of using CO_2 versus Nitrogen to dry the substrates - the CO_2 did not prove significantly better or more consistent results, therefore we recommend Headwall to continue with their current process of Nitrogen, as explained further in Section 5.4.

This conclusion results in an immediate savings for Headwall, as they can stop renting the CO_2 machine that they were using. Further, they do not need to invest in a Contact Angle Measurement tool to perform tests or experiments on the various processes, as we were able to conduct and draw conclusions through this project that gives them the confidence to continue their current process with minor efficiency modifications.

In order to perform a discounted cash flow analysis to determine the funds we saved Headwall Photonics through the work we performed we first had to estimate the current costs at

Headwall. This included the prices of aspects like scrap rate, substrates, wages of different roles, and production costs. We made estimates on other parts such as the interest rate and figured out the time period we wanted to use. See Appendix D for full estimates and discounted cash flow analysis.

5.7. Final Re-designed Testing Fixture

The original testing fixture model was not a bad design, as it did function and allow the gratings to be tested for efficiency. However, the fixture left room for error as well as space to produce defects during testing. These defects could be produced from a couple specific details of the design; thus, these points were focused on when designing the new model.

One of these points was the way in which the grating was held in the fixture by a small plastic clip that supplied force to hold the back of the grating. While this design is simple, the clip was flimsy and easy to break. In addition, the plastic clip could leave scratches when pressed onto the gratings face. To combat this portion of the design the new design plan was to create a lower contact, lower applied force fixture. This would eliminate the flimsy clip, as well as decrease the contact with the plastic to lower the chance of defects.

Another issue that was focused on when redesigning the old fixture was the way the grating was positioned in the holding. Rather than it sliding in like a slot, it balanced on two sides. This was problematic as it could easily fall off the holding when the grating was placed for testing. The reasoning behind this design was to make it easier for the operator to pick up the grating on the edges, limiting the chance for fingerprints. However, this was not always the case and often would be difficult to mount and remove.

Considering the variables mentioned above, a model needed to be designed to combat three primary areas to limit defects. The new design had to provide a more stable way to hold the grating, provide easier removal, and limit forces and contact to prevent scratches. As mentioned in the methods sections, multiple ideas and iterations were pitches that each provided different solutions to these problems. After narrowing down the simplest yet most effective way to move forward, it was decided that springs would be the best system of removal. Other automatic means of removal were good options, however were not as cost effective or necessary for the degree of accuracy needed.

As seen in Figure 16, the final CAD model was produced using 3D printing techniques. The new mount provided a better way to mount the grating, as it could slide fully into the new fixture. This prevents operators from having to worry about balancing the grating, as well as eliminating the need for the flimsy clip. This also decreases the amount of force applied directly to either face of the grating, which is the most important area to decrease defects.

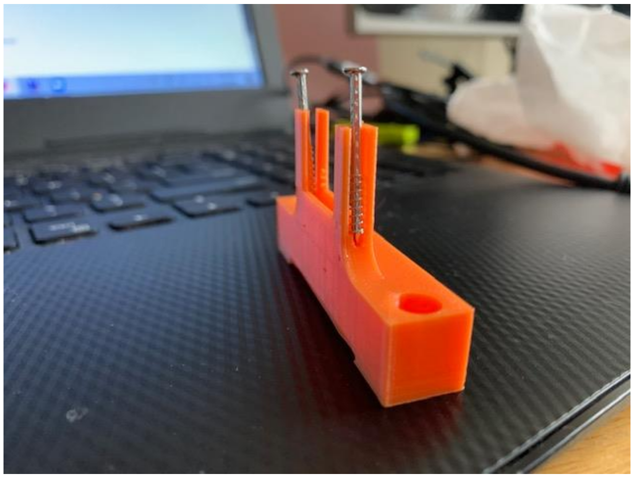


Figure 16: Final 3D Printed Fixture Prototype

In addition, springs were added to either sides of the model to help push the grating up and down. Much like a design of a toaster, the grating would slowly be released up or pushed down, providing easier access to the operator testing the grating efficiency. As seen in the 3D model, nails were used as guides to the springs. This was not done in the primary iteration, and was added after testing the model without them. With no guides, the springs often did not act in a linear path, and thus made it more difficult to remove the grating from the fixture. Moving forward one suggestion would be to machine these guides at exactly ninety degrees from the base, rather than use nails.

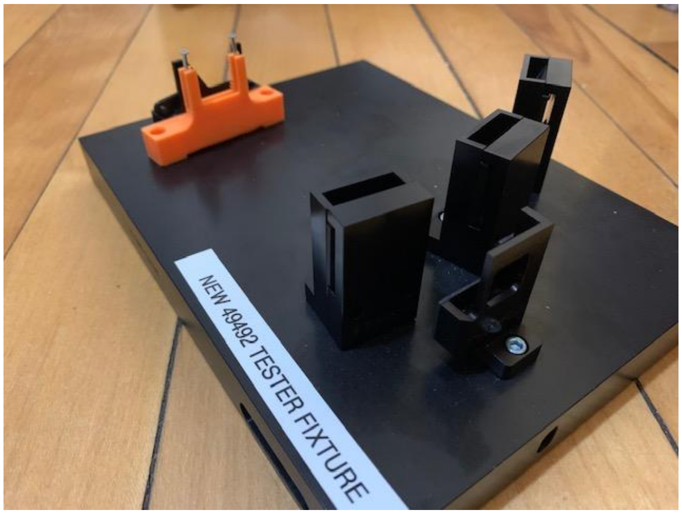


Figure 17: New 3D Printed Mount on Original Test Station

Another key variable that was kept from the old design, was the alignment and positioning of the fixture on the efficiency testing station. The angle at which the lasers hit the grating are extremely important to the usefulness of the efficiency reading. For this reason, the overall positioning was not changed, as the current positioning reported no consistent evidence of misreading.

Moving forward the entire model would be made of metal to match the current efficiency tester. Both the team and Headwall were in agreement that any machining would be outsourced by the company, therefore models were done in 3D printed PLA. If the company were to move forward with the design, the size of the springs would have to be evaluated based on the tolerancing of the machining. The springs used in the below models had a 2.3mm outer diameter, and 0.4mm inner diameter. The springs used could be larger if needed, as long as the force needed to push the grating into place feels comfortable and natural to the operator.

Figure 18: Final Fixture Model Directed at Efficiency Sensors

6. Recommendations and Technical Conclusions

After conducting tests with both the CO_2 wash and acetic acid soaks, data showed very little difference between the two initial contact angles. For CO_2, average initial contact angle was 55.3 degrees, while the average acetic acid contact angle was 54.1 degrees. From this direct comparison, the CO_2 wash does not produce any better results than the acetic acid bath. This data shows that transitioning from acetic acid to a CO_2 wash would cost more in terms of both money and time than it is worth. It is important to note that the substrates washed with CO_2 in this data set did not undergo the next steps in Headwall's process; this would have to be further tested, however the contact angle data shows that CO_2 does not result in better surface contact angles than the current acetic acid process, which disproves our original hypothesis that CO_2 would result in less corrosion to the surface.

Although the initial contact angle had very little difference, the contact angle measured after thirty seconds was much different between the two. After thirty seconds the CO_2 wash had a lower average contact angle of 47.3 degrees, while the acetic acid had an angle of 52.5 degrees. This showed that the CO_2 wash produced a substrate surface with lower surface tension than that of the normal acetic bath. While this could theoretically result in better adhesion for the photoresist later in the process, the starting contact angle is too low to be considered an improvement from the acetic acid process. Given these results, we recommend that Headwall continues with their current pre-clean process involving acetic acid, rather than switching to a CO_2 process. With this, we further recommend that they discontinue renting their current CO_2 machine and implement the following modifications to their current process to improve their scrap rate, reproducibility, and repeatability.

1. Implement a CONWIP pull system to improve forecasting, therefore efficiently of product planning and production
2. Utilize the provided standardized work instructions (Appendix A)
3. Incorporate our proposed design to the testing fixture to replace the current load/unload mechanism, as a way to decrease operator touch time and limit the possibility of damaging the substrate, therefore improving yield and cycle time

Based on the various methods we took to analyze Headwall's current processes and resources; the following table summarizes our corresponding results and recommendations.

Table 4: Recommendations and Conclusions

Methods	**Results**	**Conclusion**
Axiomatic design	Decomposition of process; identified if goals could be accomplished independently and order of operations for pre-clean process	Pre-clean process should follow very specific instructions to avoid over-processing
Value stream mapping	Developed a more efficient value stream map by eliminating non-value-added time where possible	Headwall can utilize this to decrease waste and improve efficiency, further resulting in cost savings
Lean manufacturing	Recommended CONWIP system implementation to Headwall	Due to COVID-19 we could not implement it at the facility ourselves, but have provided Headwall with a plan to do so in the future
Data collection/direct simulation of process	Identified areas in process instructions that could be more clear; Fine-tuned process to result in optimal contact angles	New process instructions will eliminate tribal knowledge and variances between operators; New process map will lower corrosion of the surface and improve yield during the photoresist process.

Contact angle	CO_2 process and Acetic Acid process affect the contact angle of the substrate's surface similarly	Continue using Acetic Acid process; discontinue renting the CO_2 machine; do not need to spend further efforts experimenting with CO_2
Seven wastes	Reduced waste in pre-clean processed and recommended ways to reduce waste in pull system	By eliminating over-processing and transportation, waste is reduced
Cost benefit	Through testing we figured out a more efficient system for Headwall to use	We saved Headwall labor and material costs
Plasma application	Parts were sent to Drexel University to the Plasma Institution	Due to delays and COVID-19 obstacles throughout the year, we have not yet received results; Headwall and Drexel point of contacts identified so they can continue communications
Prototyping and iterations	A new fixture design for the testing process that decreases human touch and improves the ease of loading/ unloading parts	After implementation of this design, Headwall will see lower scrap rates and improved efficiency
Gage R&R	Allows data to drive Quality control; able to identify parameters to have corresponding corrective actions if they meet at a certain level	Waste will be mitigated in both workforce capital and recycling of substrates in the pre-clean process.

7. Conclusion

Our team was faced with both a technical and abstract problem and worked collectively as a team of diverse disciplines to solve a real-world problem for a company that will assist their success in the long run. Our team worked well together because we were always open to each other's ideas as well as any adjustments we needed to make to the project. As a team we worked on solving a problem from the start: defining the problem, hypothesizing, experimenting, concluding in an atypical scenario mostly through online meetings. We did the experiments so we could verify what we did would work for Headwall. Due to this project being mostly virtual, we had to be very flexible during this project as we felt this was essential when completing an almost yearlong project with a company when you cannot physically be on site. We each felt we made a difference in Headwall first getting an understanding of how the company ran and then brainstorming what we learned in our classes that could align with aspects of Headwall running more efficiently and effectively.

Going forward we now have valuable tools we have learned through this experience about the difficulties you face when working with a company in an unusual circumstance along with trying to make your ideals for a project align with the company ideals. MQP has been a strong learning experience, especially with the unusual obstacles we faced this year. We learned that applying concepts from our curriculum is not always straightforward in the workplace. There are many variables and challenges that exist. Without being onsite at that company it is difficult to see and experience those factors in order to know what is best for the company. A huge benefit was learning how to intertwin the different fields we study and becoming comfortable asking for help from both Headwall and our Professors. We have even had to become comfortable asking for help in our group as we have management, industrial, and mechanical engineers all with different backgrounds and parts of the project were in optics, chemical, material, and lean manufacturing for Headwall. This enabled us to identify and develop solutions that had potential to help Headwall. Working with individuals at Headwall that had experiences in a variety of areas was also helpful. For example, the manufacturing manager knew the processes, the director of manufacturing and operations understood the operations, and the materials manager knew the supply chain. Our team learned technical, operational, and efficiency skills that we can take into our roles after graduation. We learned how to apply our concepts in a real manufacturing setting, and got to experiment with what worked and what did not which prepares us for working in the professional world. This will be a lifelong learning aspect for us because of the opportunity our team had to apply the education from our undergraduate to a developed company.

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Appendices

Appendix A: Steps for Completing Pre-clean Process

PREPARATION FOR PROCESS

1. Retrieve new glass from inventory storage
2. Put on gloves (proper attire)
3. Fill three clear plastic bins each with 2000 mL of H_2O
    a. For the first bin add 100mL of developer solution (acetic acid)
    b. For the second bin add 50mL of developer solution
    c. The third solution should be pure H_2O
4. Prepare ultrasonic
    a. Fill halfway with acetone
5. Fill wash bottle halfway with methanol

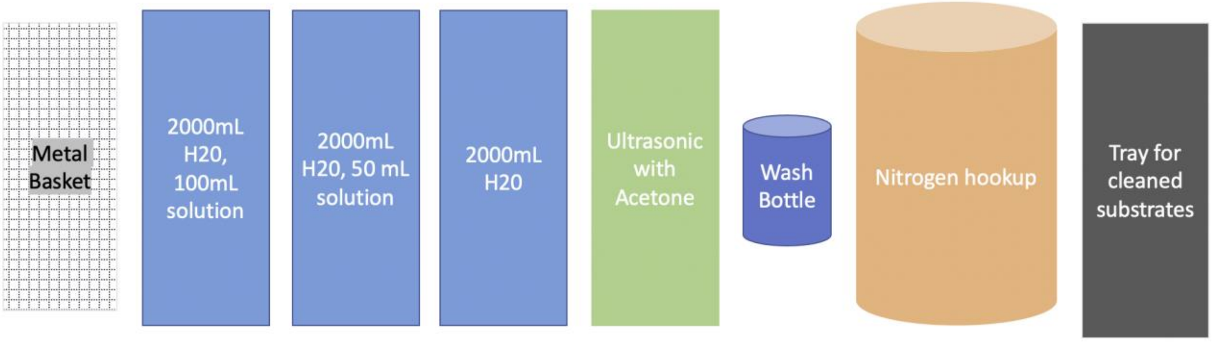
BEGIN PROCESS

1. Take one batch of new glass and place in metal bin
2. Place metal bin in H_2O and 100mL solution for 1 minute (use timer)
3. Move metal bin to H_2O and 50mL solution for 1 minute (use timer)
4. Move metal bin to pure H_2O bath for 1 minute (use timer)
5. Move metal bin to ultrasonic bath for 2 minutes (use timer)
6. Repeat steps 2-4
7. Rinse batch with methanol making sure to cover all surfaces of each piece
8. Blow dry the entirety of each piece with nitrogen hookup (make sure to only hold the sides of the glass)
9. Place in correctly labeled tray when completed

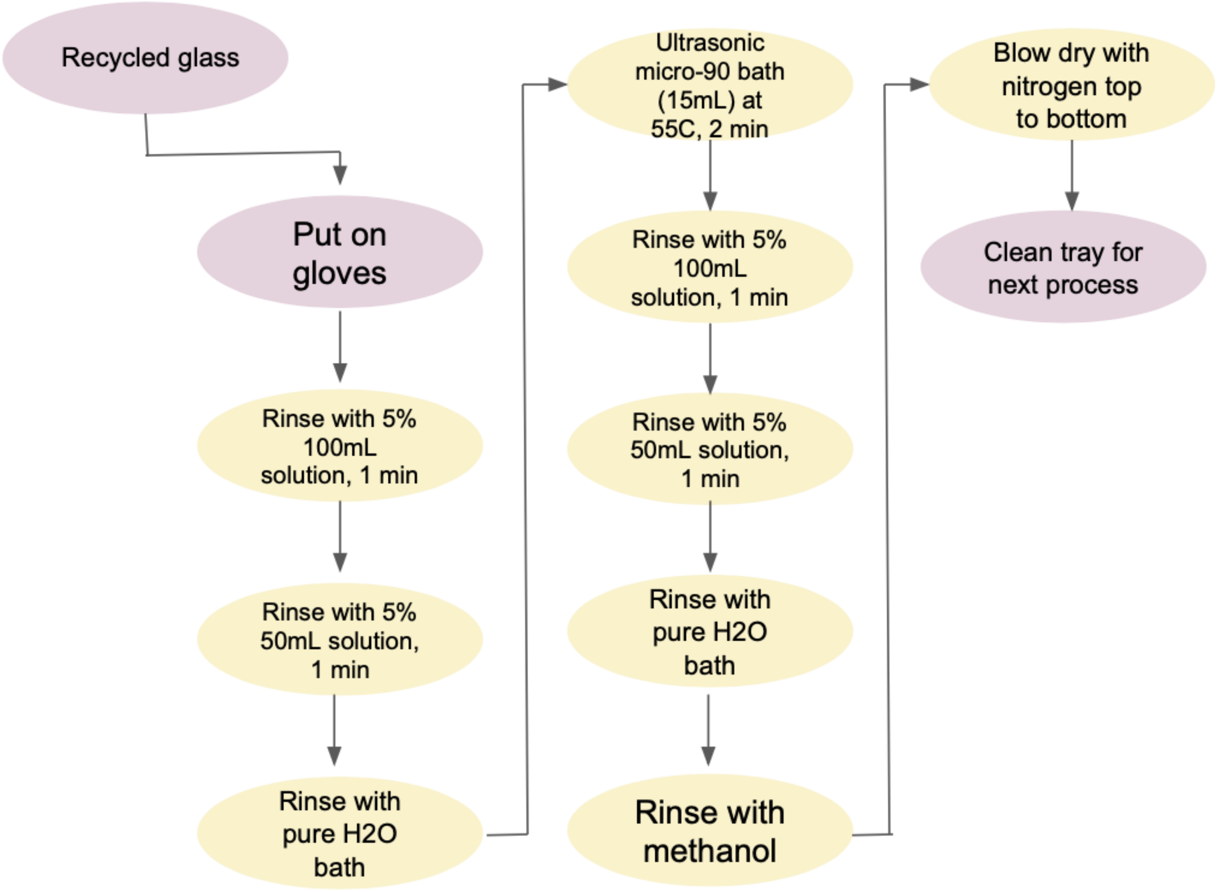
POST PRE-CLEAN

1. Clean trays for next process

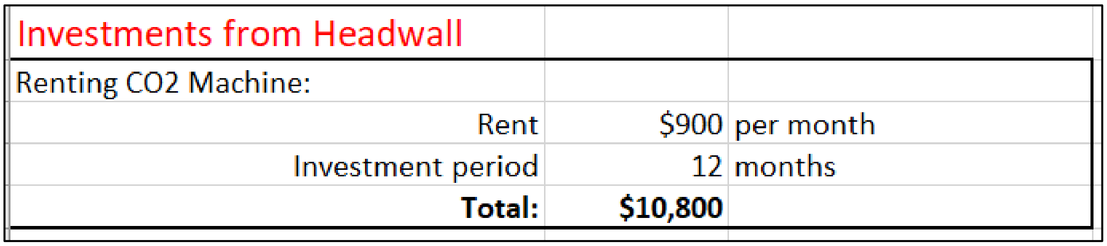
Appendix B: Diagram of Pre-clean Setup



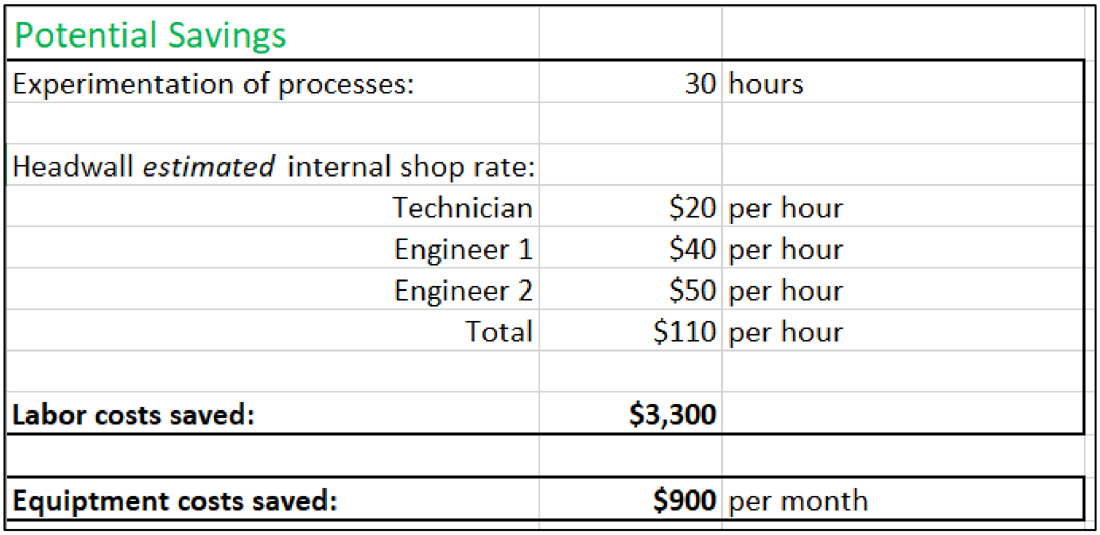
Appendix C: Standardized Pre-clean Process



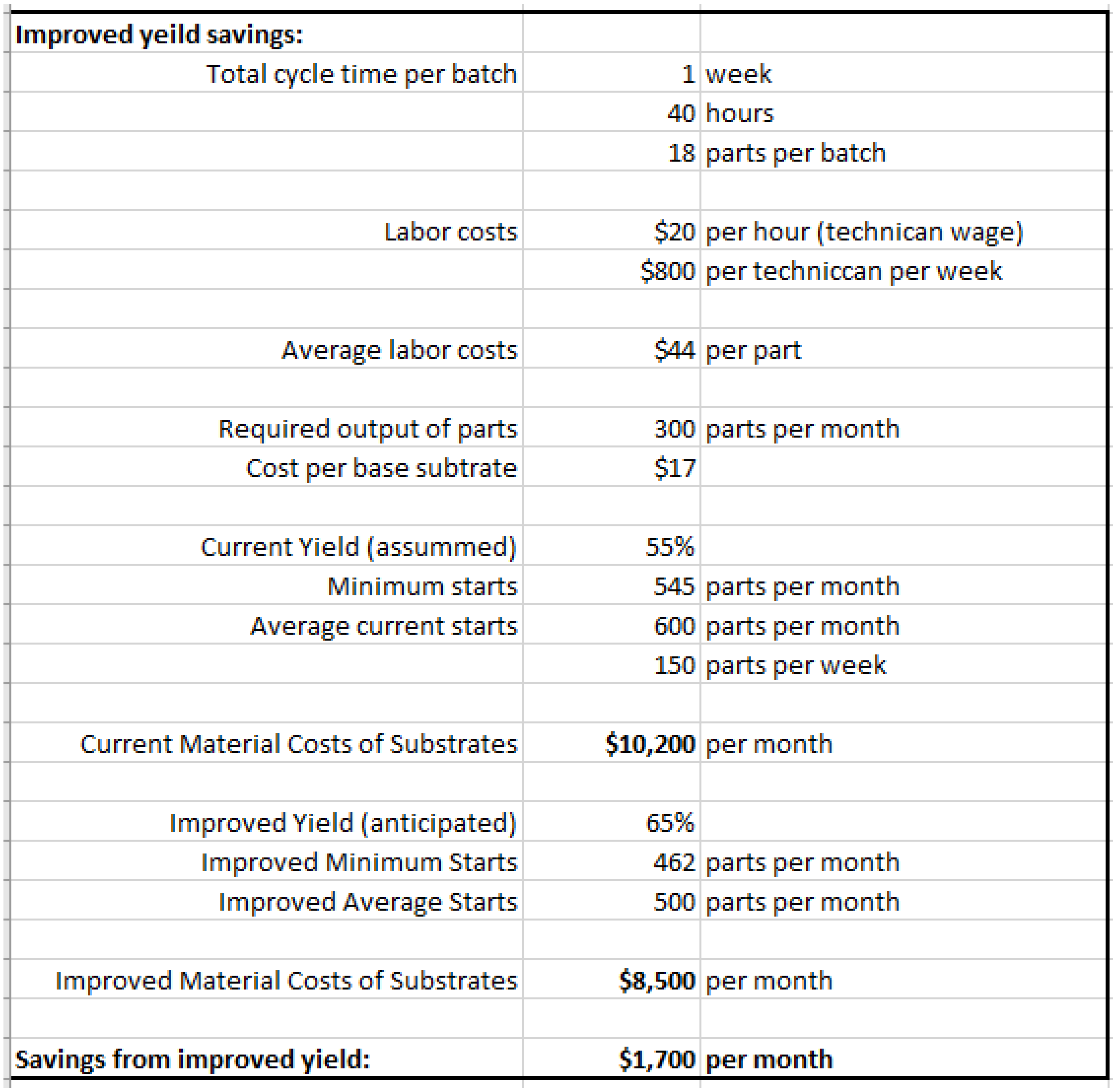
Appendix D: Time Value Money Analysis



Investments from Headwall		
Renting CO2 Machine:		
Rent	$900	per month
Investment period	12	months
Total:	**$10,800**	



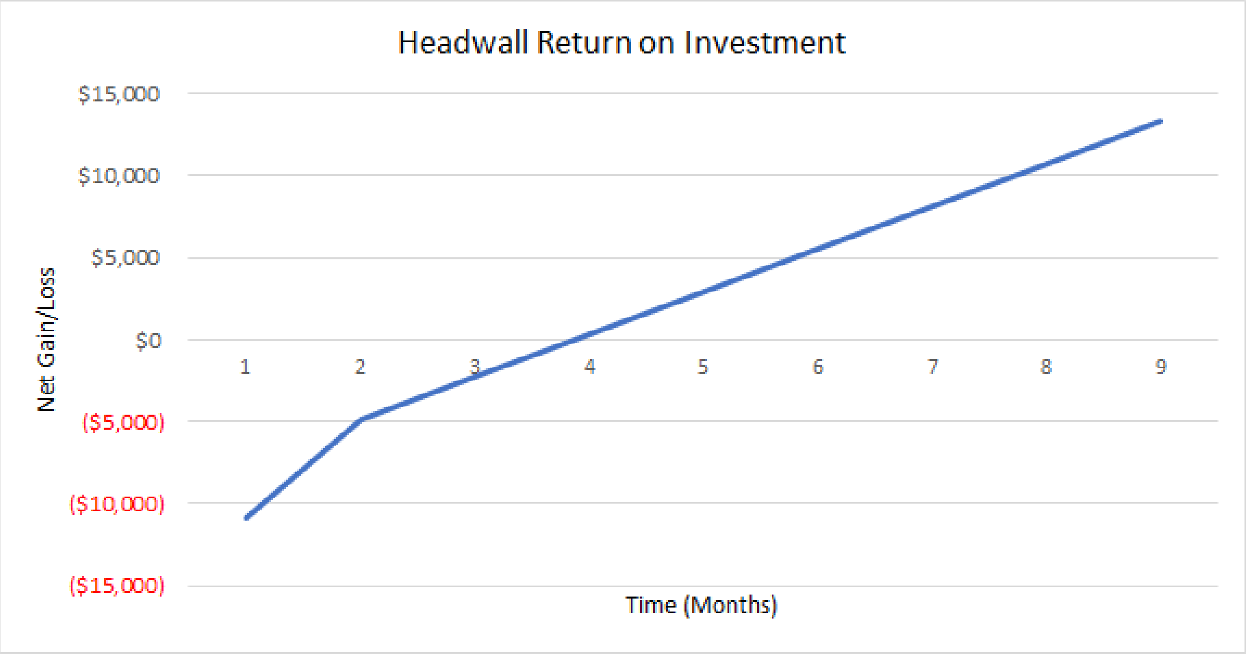
Potential Savings		
Experimentation of processes:	30	hours
Headwall *estimated* internal shop rate:		
Technician	$20	per hour
Engineer 1	$40	per hour
Engineer 2	$50	per hour
Total	$110	per hour
Labor costs saved:	**$3,300**	
Equiptment costs saved:	**$900**	per month



Improved yeild savings:		
Total cycle time per batch	1	week
	40	hours
	18	parts per batch
Labor costs	$20	per hour (technican wage)
	$800	per techniccan per week
Average labor costs	$44	per part
Required output of parts	300	parts per month
Cost per base subtrate	$17	
Current Yield (assummed)	55%	
Minimum starts	545	parts per month
Average current starts	600	parts per month
	150	parts per week
Current Material Costs of Substrates	**$10,200**	per month
Improved Yield (anticipated)	65%	
Improved Minimum Starts	462	parts per month
Improved Average Starts	500	parts per month
Improved Material Costs of Substrates	**$8,500**	per month
Savings from improved yield:	**$1,700**	**per month**

Required Rate of Return:	10%
Need to Break-even	$11,880
Inflation	2.5%
Need to Break-even (w/ inflation)	$12,177
Achieved by	Month 8

Months	0	1	2	3	4	5	6	7	8	9	Total
Money spent	($10,800)										($10,800)
Money saved	$3,300	$2,600	$2,600	$2,600	$2,600	$2,600	$2,600	$2,600	$2,600	$2,600	$26,700
Net Gain/Loss	($10,800)	($4,900)	($2,300)	$300	$2,900	$5,500	$8,100	$10,700	$13,300	$15,900	$38,700
Discounted Cash Flow	($10,800)	($4,780)	($2,189)	$279	$2,627	$4,861	$6,985	$9,002	$10,916	$12,732	$29,631
NPV	$29,631										


Headwall Return on Investment
$15,000
$10,000
$5,000
$0
($5,000)
($10,000)
($15,000)
Net Gain/Loss
1
2
3
4
5
6
7
8
9
Time (Months)