High Volume Machining Analysis

A Major Qualifying Project Report
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Abstract

The objective of this MQP was to reduce non-value added time during the machining of a high volume part for the project sponsor JAZ Manufacturing. Direct observation and measurement of the machining process was performed to gain understanding and determine any problems. The methods used included value stream mapping, axiomatic design, Taylor’s tool life equation and engineering economic analysis. Decomposing the functional requirements of machining the part showed that a significant reduction in machining time was possible. The conclusion shows that an analysis of non-value added time, along with the application of the best practices in machining can yield a large reduction in processing time, increased productivity, and substantial savings for the company.

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Chapter 1: Introduction

1.1 Project Objective

Our objective of this project was to increase the overall efficiency of the machining process of the FBAR packages. JAZ Manufacturing is a global leader in the design and manufacture of solid state laser systems for industrial applications. They are headquartered in Oxford, MA, where our project takes place. JAZ desires to improve certain areas of their manufacturing process, and our objective is to ensure that their manufacturing process is as efficient as possible. The main goals of JAZ Manufacturing as a corporation are to accelerate development, meet customer needs, manage costs, and maintain high performance and quality standards. One way for the company to meet these requirements is to improve their machining efficiency.

Our project specifically focuses on the machining of a part known as FBAR packages (Appendix D). JAZ manufactures, on average, 1,200,000 of these pieces per year. They are in high demand and are currently the bottleneck of a much larger process. Over time, a very small reduction of machining time would help relieve the bottleneck leading to higher throughput and reduced costs.

1.2 Value Proposition

The key to creating value is to provide a product or service that customers want as efficiently as possible. Quality is not limited to greater durability or excellence in design, but it also supports the customer’s specific needs, or the requirements. Within every process there are two elements, those that add value and those that add no value, which is known as waste (Amin, 2013). It is essential to determine the difference between value added and non-value added steps in order to reduce costs.

Toyota defines waste as “anything other than the minimum amount of equipment, materials, parts, and working time absolutely essential to production” (Amin, 2013). A way to better define value added might be an activity that physically changes the shape or character of a product or assembly that adds value. In turn, any activity that does not change the product or assembly is waste. Consider the case of a roughing cut in machining, one that changes the character and shape of the product but is not necessarily the most efficient use of production time. Therefore, every activity should be considered to be waste unless it meets an explicit requirement and cannot be shown to be performed more economically (Trent, 2000).

When examining each step of the process of machining FBARs some of the things that we kept in mind are whether the step was changing the form or character of the product, or if it was meeting an explicit customer requirement. If it was doing either of those, then we considered if there were a more economical way to perform that step. This is where the many lean manufacturing tools one uses to help identify those steps that do not add value and so they can be eliminated. There are a number of different ways to identify value as well as non-value adding steps. We developed a value stream map, as shown in figure 1, to highlight the different steps in the process (Chen, 2010).

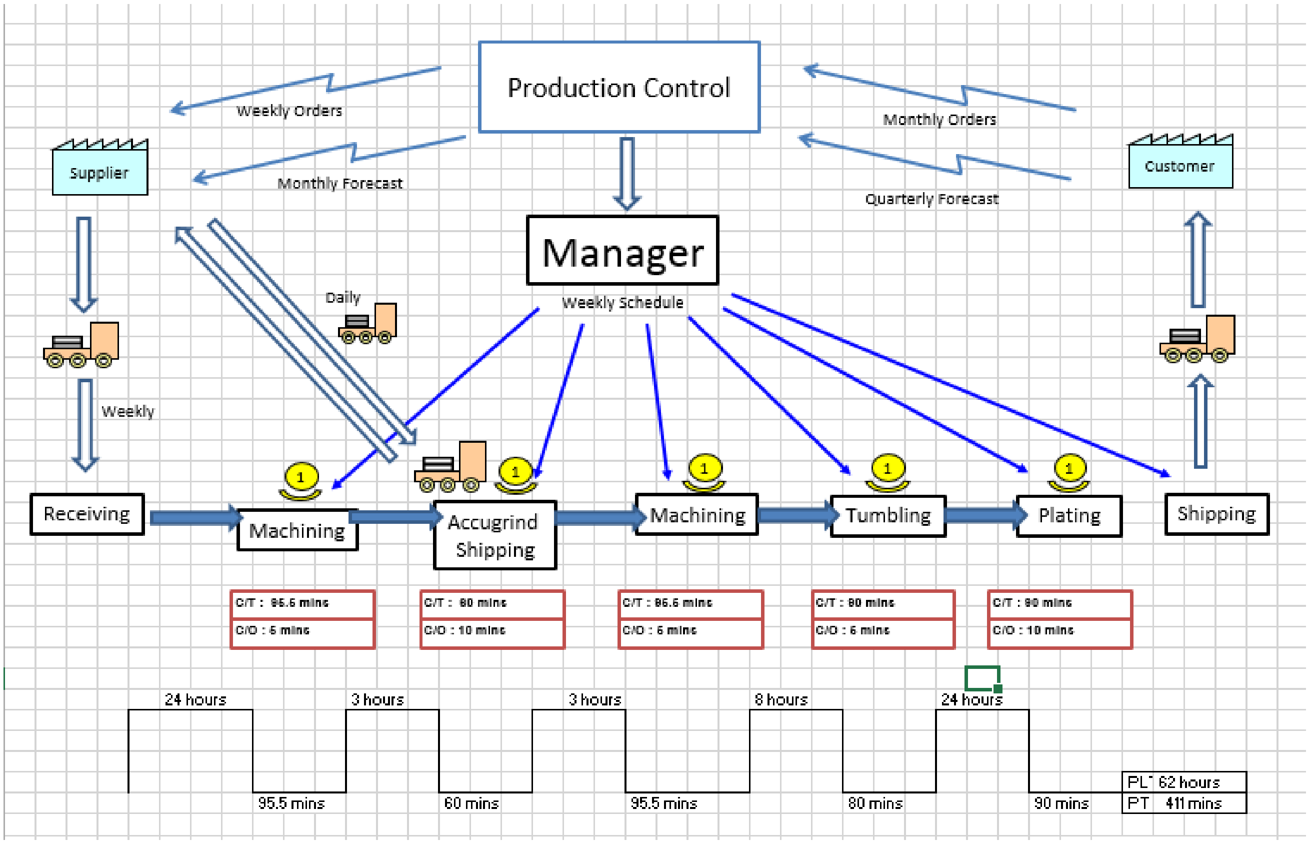


Figure 1: Value Stream Map of FBAR Machining Process

Chapter 2: Manufacturing

In order to make their production lines more lean while retaining high customer satisfaction, most manufacturers aim to reduce or eliminate unnecessary production costs and wasted production time. Companies can provide a better product at a lower price if they run production operations smoothly and efficiently. One way a manager can measure the efficiency of a production line is by examining the cycle time.

Cycle time measures the amount of time it takes to produce a product. Cycle time includes value added process time, inspection time, move time, and wait time. All of these processes are part of producing one product. The inspection time, move time, and wait time are considered to be non-value adding processes. For example, inspecting a part for flaws or moving it to the loading dock does not improve the part. In other words, these processes don't add value to the product. The only added value in the FBAR machining process is when tools are changing the part. Production time has value added and non-value added time as it creates a product from raw materials. The product is improved by the end of the machining cycle time. With cycle time being a major focus of our project, we determined that there are two ways to ensure the fastest cycle time, which are optimizing the machining program and equalizing the cycle time between multigenerational CNC machines for load balancing.

In JAZ’s production process, there are a number of inputs involved. Property in the form of building and infrastructure, machinery, labor, raw materials, and consumables support the production process. Many of these inputs are constraints, meaning they have limits, and are not able to be increased easily. The machining space in Oxford, Ma is not able to be expanded without moving to a new location. Additionally, their machine shops are filled to capacity. This is where efficiency of production operations is extremely important. By maximizing the efficiency of the FBAR machining processes, JAZ will significantly reduce costs. . The machining time and consumable tools are the main way to increase the output of a product in high demand. This includes optimizing the operation of the CNC machines themselves, as well as improving the program that runs the CNC's. We came to this conclusion after gathering data and observing the process, as well as guidance from Michael Grasis, the operations manager, and Eric Johnson, the production manager. Since the machining process is such a large input of processing time, eliminating any other waste would result in minimal to no added value to the overall process. By reducing and balancing the CNC cycle times, optimizing the machining programs, and reducing their consumable tools, JAZ will reduce costs on the FBAR Packages.

2.1 Overview

The main goal of our project is to improve the overall efficiency of the machining process of the FBAR packages within JAZ Manufacturing. We achieved this goal through reducing cost and time of the process. To reduce cost, cycle times were analyzed in addition to using Taylor's Tool Life equation to maximize the tool life while also minimizing work in progress (WIP) inventory. The cycle time can be reduced through analyzing the machining programs, optimizing the speeds and feeds of the program and standardizing the machining parameters unique to each CNC machine. Another objective is to balance cycle times between multi-generational CNC machines, to help JAZ produce at takt time.

2.2 FBAR Functionality

The FBAR is a device that receives electrical input from the two “pins” on the side, and produces a stable optical output that is contained in the optical fiber pigtail, which is coiled in green and shown in Figure 2 (JAZ, 2015).

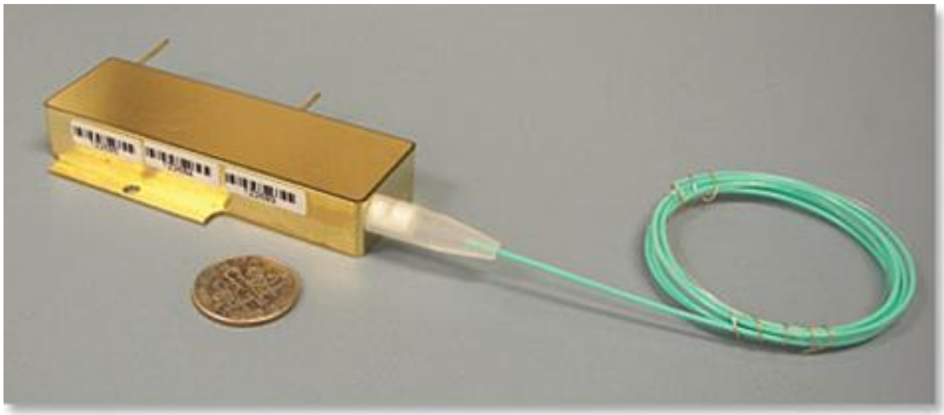


Figure 2: Complete FBAR Package

The package is machined and is then gold plated before assembly, shown in Figure 2. There are electrical pin and optical fiber feedthru’s, along with optical, electrical, and mechanical components that are all assembled within the packages. After this assembly, the lid is welded on and the assembly becomes sealed. These parts are in extremely high demand and the company has a certain status quo to meet regarding their machining. Any reduction in machining time would be essential to the company. Below is the CAD drawing of the FBAR that our team produced. They must be machined dimensionally accurate in order to function correctly.

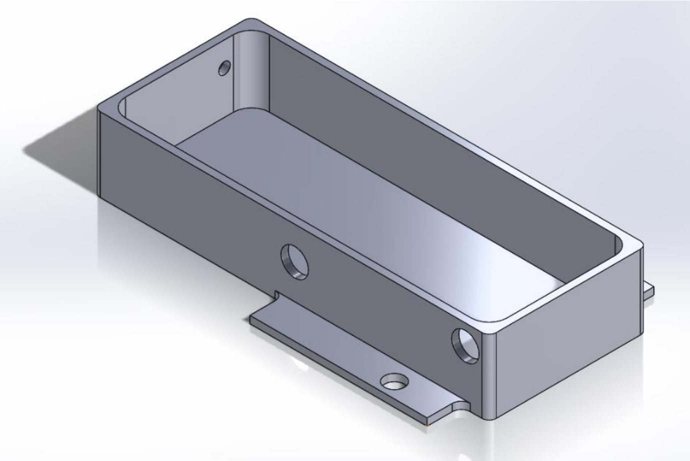


Figure 3: FBAR Part Drawing Pre Plating

2.3 FBAR Production Process

To achieve the goals and objectives of the project we tried to understand JAZ's needs to increase throughput. A description of the total process from raw material to finished product follows. JAZ purchases raw steel stock material from a local distributer. The material, A36 hot rolled steel, is purchased in 10 foot long bars and sent to a local metal grinding company. This company grinds and cuts the metal to 7 inch long individual bars, which are then delivered to JAZ, shown in Figure 4.

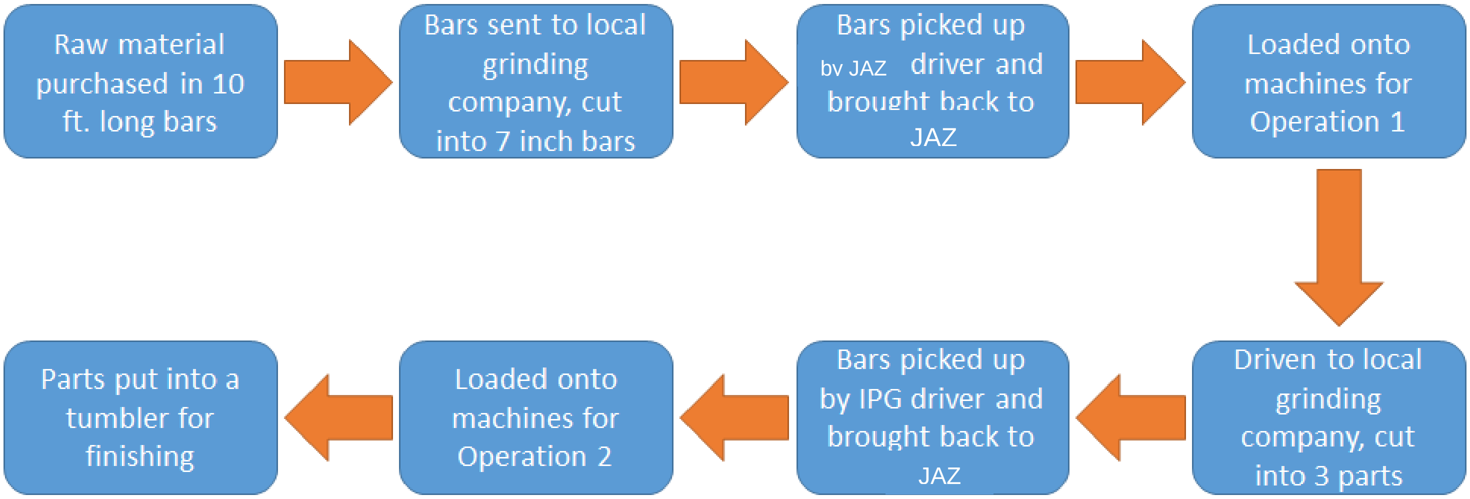


Figure 4: FBAR Manufacturing Process

The length of the raw stock bars is a variable that we cannot change. It was determined by JAZ and the vender that 7 inch bars are the maximum size the steel can be produced. At JAZ, the bars are unloaded and kept in a nearby open stock room, where they are stored prior to being machined. When ready, the bars are loaded into a Mazak HCN 5000 horizontal milling machine, shown in Figure 5.

Figure 5: MAZAK Horizontal (HCN 5000)

This is the start of the individual part's machining process. The machining process is separated into two different operations, Operation 1 and Operation 2, as shown in Table 1.

Operation 1	Roughing, Pocketing, Finishing
Operation 2	Drills one final hole in the side

Table 1: Operation Descriptions

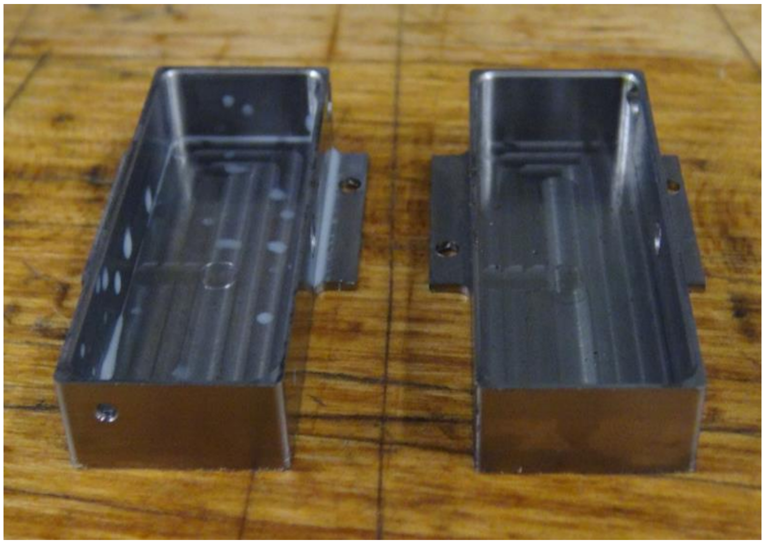


Figure 6: Operation 2 Completed (left) Operation 1 Completed (right)

Once the first operation is completed, they are then considered to be “half-finished” and are delivered back to the local grinding company. There, the bars are ground to size and are separated into individual unfinished parts. These individual parts are brought back to JAZ where they are loaded back into the CNC machine to finish machining the part during Operation 2. It may appear that this step in between the machining process would affect the efficiency of the overall process, however, if eliminated, it would not greatly reduce the overall processing time. The bottleneck in this process is the machining of the part itself. JAZ has taken steps to make the machining as efficient as possible where, according to management, if improvements of 200% were made in those areas, the overall process improvement would be minuscule. It also should be noted that JAZ has strongly recommended that any improvements in the overall process will result from improvements within the machining process itself. Once this machining process is done, the individual parts are unloaded from the machine and then loaded into tumblers. The tumblers deburr and dry the part, ensuring that there are no sharp edges prior to assembly. The parts are then inspected and packaged. Once packaged, they are sent off to an outside supplier for gold plating. After plating, the parts are complete and ready to be delivered to the JAZ stockroom, where they wait to be assembled. This process can be completed multiple times per day.

2.4 Machining Process

Due to space limitations, JAZ is at the maximum number of CNC machines that is available. A machine is loaded with both raw stock steel bars and parts that are nearly finished but need a second operation performed. Each machine has two pallets, one that is being loaded and one that is being machined on. Each CNC machine is loaded with 12 bars of raw stock that are ready for the first operation and 40 half-finished parts that are ready for the second operation. One complete machining cycle performs both Operation 1 and Operation 2, producing 36 half-finished parts and 40 fully-machined parts. Figure 7 shows the raw stock (top), a completed Operation 1 piece (middle), and the finished pieces after Operation 2 (bottom). The pieces are separated at an outside grinding company and returned for Operation 2 which just taps a small hole (Figure 6). There are a total of 6 machines that are running 24 hour per day.

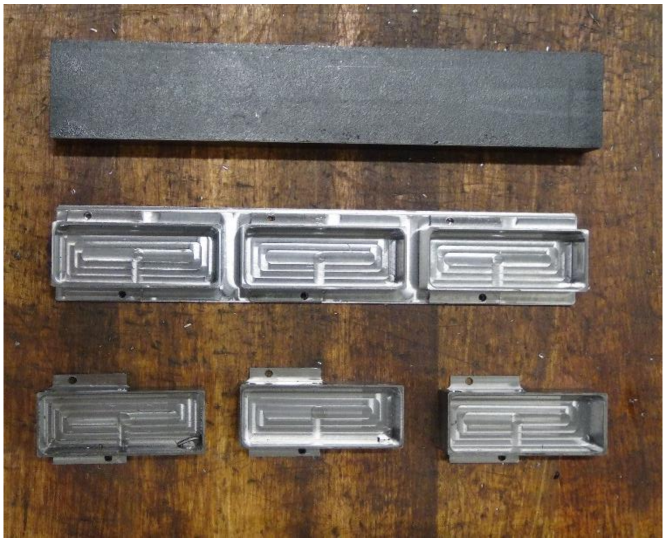


Figure 7: Raw Stock to Finished Part

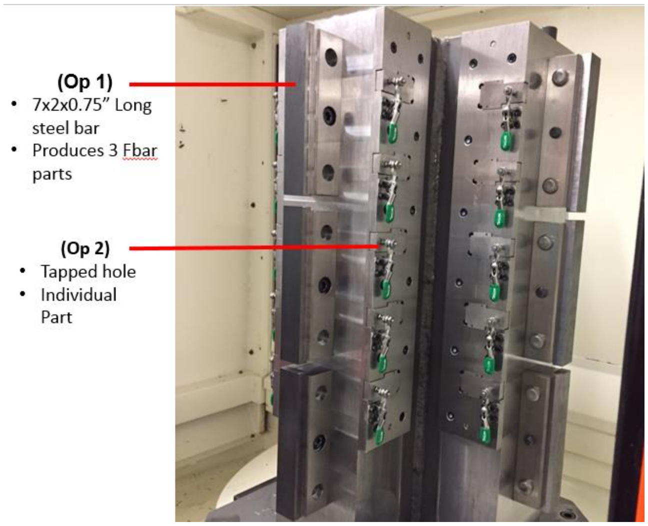


Figure 8: Loaded Pallet Ready for Machining

Data was collected from machine operators to find each of the 6 machine's average cycle time. Average cycle times range from machine to machine from about 3 hours and 11 minutes to 3 hours and 40 minutes, as shown in Table 2.

Machine Number	Average Cycle Time
MH-2	**3 hours, 28 minutes**
MH-3	**3 hours, 15 minutes**
MH-4	**3 hours, 40 minutes**
MH-8	**3 hours, 11 minutes**
MH-9	**3 hours, 29 minutes**
MH-10	**3 hours, 14 minutes**

Table 2: Machine Cycle Times

Also, broken tools can cause a delay in a cycle and those extraneous cycles take a little over 4 hours. There are a total of 13 tools (Appendix G) that are used to produce the FBAR packages. According to management, JAZ has standardized the tool change process over time. This is something that has been optimized from their experience over many years through trial and error. All of the machining tools (# 2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 15, 16,17) are changed every 15 cycles. In addition to the major change every 15 cycles, half of the tools (# 2, 3, 4, 5, 6, 7, 8, 15) are changed every 5 cycles.

Chapter 3: Methods

3.1 A Lean Approach

Maximizing value added while eliminating waste is known as a lean process improvement (Cox, 2015). The most well-known types of wastes related to manufacturing are those described by the Toyota Production System, which consist of transportation, waiting, motion, excess inventory, overproduction, over processing, and defects (Belekoukias, 2014). To achieve the goal of improving the efficiency of machining the FBAR, we sought to minimize these types of waste. In a lean system, the goal is zero waste. We applied the seven wastes in manufacturing at the scale of the machining center itself.

The waste of transportation refers to how the actual part moves around the production floor. The more three dimensional transportation movement of the physical part, the more likely it is to get damaged. Transportation is a non-value added process being simply moving the part around the floor does not add value to the part.

Motion refers to how the machines or the operators work and travel. For example, if the operator is doing a process that requires them to zigzag all around the floor that would not be an example of lean manufacturing. A lean process improvement would be to alter the floor layout so that the operator would have to move around less, or put less human effort. Motion can also refer to the machining process itself and tool paths of the machines.

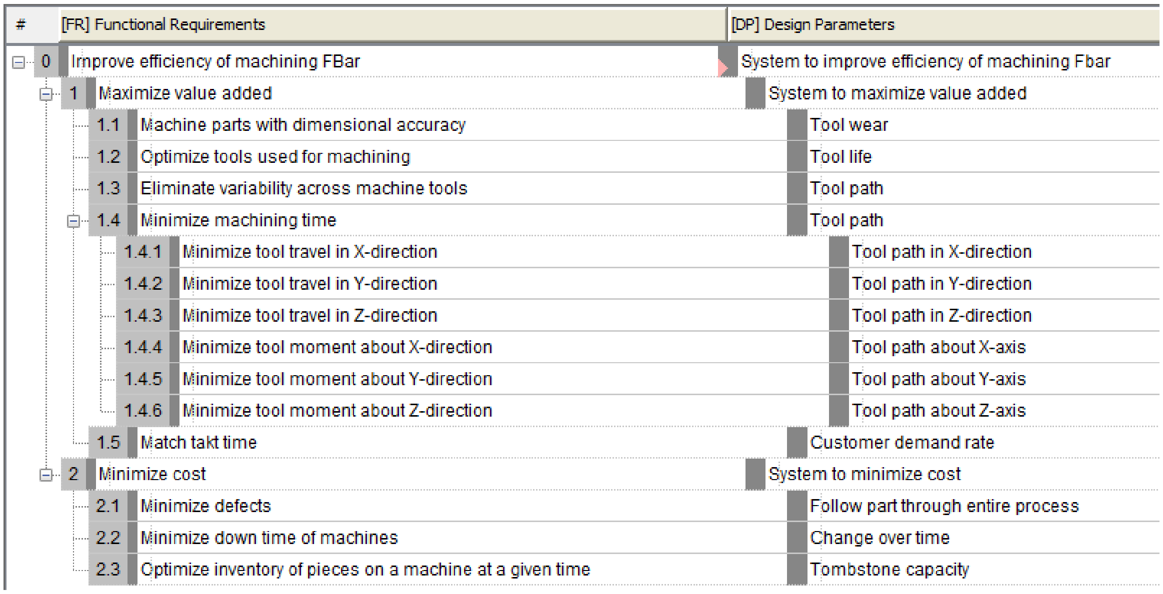
Waiting is a form of waste because nothing is happening during that time, and there is no value being added.

Other wastes are over processing and overproduction. If more work is done on the FBAR than is required, it is wasteful and not needed. It would take up extra time that could be used for doing other tasks. Overproduction is wasteful because if you produce more than you need, there is excess inventory built up. That inventory would then need to be stored, which can create extra costs. Also, building before customer demand means that production resources that are consumed cannot be recovered or used on other parts.

3.2 Axiomatic Design

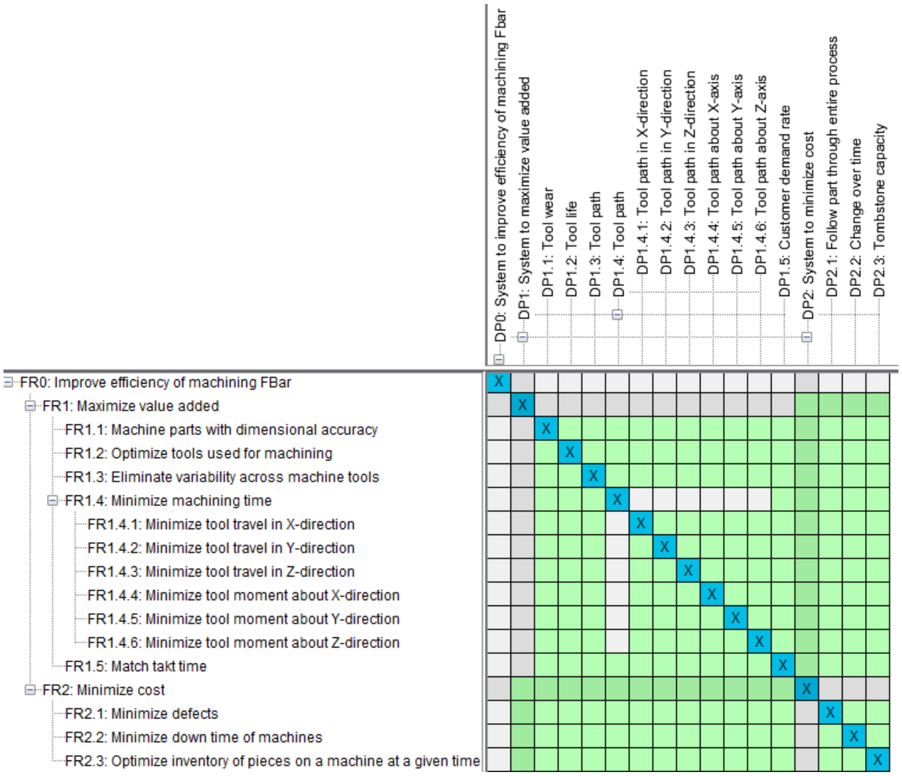
Axiomatic design is a problem-solving approach that uses matrices to show how functional requirements (FRs) and the design parameters (DPs) are related. There are two axioms that must be followed: the independence axiom and the information axiom (Suh, 1990). The independence axiom states that the FRs must be mutually exclusive. The information axiom states that the amount of content of the final design must be minimal. In other words, maximize the independence of the functional element and minimize the information content in a design.

For our project, the highest level function requirement (FR0) is to improve the efficiency of machining the FBAR. This means that the ultimate goal or end result is to improve the overall efficiency. The children FRs (FR1 and FR2) consist of maximizing value added and minimizing cost. Our team came up with five ways that could help increase value added, which were to ensure dimensional accuracy, optimize the tools, eliminate variability across the tools, minimize machining time, and match the takt time. Some of these were difficult to decide if they satisfied maximizing value added or minimizing cost. For example, reducing the machining time we identified as value added, even though others may see it as minimizing cost. We decided it fits better under maximizing value added because a machine is only adding value to the piece when the tool is physically touching and cutting the part. Tool changes and tools moving around in the machine are not adding any value. Therefore, reducing the machining time would mean that more time is spent adding value. In order to minimize cost, the defects and down time of the machines should be minimized, and the inventory of parts on a machine should be optimized.



#	[FR] Functional Requirements	[DP] Design Parameters
0	Improve efficiency of machining FBar	System to improve efficiency of machining Fbar
1	Maximize value added	System to maximize value added
1.1	Machine parts with dimensional accuracy	Tool wear
1.2	Optimize tools used for machining	Tool life
1.3	Eliminate variability across machine tools	Tool path
1.4	Minimize machining time	Tool path
1.4.1	Minimize tool travel in X-direction	Tool path in X-direction
1.4.2	Minimize tool travel in Y-direction	Tool path in Y-direction
1.4.3	Minimize tool travel in Z-direction	Tool path in Z-direction
1.4.4	Minimize tool moment about X-direction	Tool path about X-axis
1.4.5	Minimize tool moment about Y-direction	Tool path about Y-axis
1.4.6	Minimize tool moment about Z-direction	Tool path about Z-axis
1.5	Match takt time	Customer demand rate
2	Minimize cost	System to minimize cost
2.1	Minimize defects	Follow part through entire process
2.2	Minimize down time of machines	Change over time
2.3	Optimize inventory of pieces on a machine at a given time	Tombstone capacity

Figure 9: Axiomatic Design Decomposition



	DP0: System to improve efficiency of machining Fbar	DP1: System to maximize value added	DP1.1: Tool wear	DP1.2: Tool life	DP1.3: Tool path	DP1.4: Tool path	DP1.4.1: Tool path in X-direction	DP1.4.2: Tool path in Y-direction	DP1.4.3: Tool path in Z-direction	DP1.4.4: Tool path about X-axis	DP1.4.5: Tool path about Y-axis	DP1.4.6: Tool path about Z-axis	DP1.5: Customer demand rate	DP2: System to minimize cost	DP2.1: Follow part through entire process	DP2.2: Change over time	DP2.3: Tombstone capacity
FR0: Improve efficiency of machining FBar	X																
FR1: Maximize value added		X															
FR1.1: Machine parts with dimensional accuracy			X														
FR1.2: Optimize tools used for machining				X													
FR1.3: Eliminate variability across machine tools					X												
FR1.4: Minimize machining time						X											
FR1.4.1: Minimize tool travel in X-direction							X										
FR1.4.2: Minimize tool travel in Y-direction								X									
FR1.4.3: Minimize tool travel in Z-direction									X								
FR1.4.4: Minimize tool moment about X-direction										X							
FR1.4.5: Minimize tool moment about Y-direction											X						
FR1.4.6: Minimize tool moment about Z-direction												X					
FR1.5: Match takt time													X				
FR2: Minimize cost														X			
FR2.1: Minimize defects															X		
FR2.2: Minimize down time of machines																X	
FR2.3: Optimize inventory of pieces on a machine at a given time																	X

Figure 10: Axiomatic Design Coupling matrix

3.3 Observations

The shop floor where the FBAR packages are made is kept very neat with very little clutter and hardly any free space whatsoever. JAZ is challenged to meet takt time to keep up with their production. They have squeezed 6 machines into this space. The building was organized and we knew an additional machine would not fit and could not be a potential solution. We carefully observed each step involved in the process from the operators loading and unloading parts, to the individual steps of the machining process. The machine operators were responsible for attaching the stock and removing the finished pieces as well as transporting stock and finished pieces. We came to the conclusion early on that the flow of the workspace and the operator’s timeliness were not issues that JAZ wanted us to focus on.

In order to come up with a plan to reduce the machining time we needed to take a closer look at their manufacturing process to really gain an understanding of what was going on. We examined each machines tool-change logs and saw that there was a set system for when tools would be changed, but it was not necessarily optimized for each tool. (Appendix C) Each change was for a large group of tools and for many tools, the change was premature in order to avoid breakage on a tool that might not last as long. We analyzed data on average cycle times for each machine to compare the slowest and the fastest machines. (Appendix D) We then observed the specific steps of the process to find data to compare the duration of the individual steps between the two machines. We wanted to see if a specific step or set of steps were the reason for the large discrepancy in cycle times (Appendix E).

From the machining step time data we saw that 2-3 steps in the process were responsible for some of lag on the slower machine. The rest of the extra time could not be determined. This required the machine manufacturer, Mazak to get involved as we were told this was due to parameter settings specific to each CNC machine.

3.4 Time Studies

3.4.1 Cycle Times

One of the main objectives of this project was to reduce the cycle time of the machining process. In order to do that, we conducted several time studies to analyze the current cycle times. JAZ has six different machines that are constantly running to produce the FBAR. Since the cycle times are a few hours long, we assigned operators the task of recording the start and end time of a cycle on each machine. For more accuracy, the cycle times were recorded for three cycles per machine and then averaged to find the cycle time of each machine. Ideally, all the machines would have the same cycle time since they are all running the same program.

3.4.2 Machining Step Times

The next time study that was conducted was how long each individual machining step took. The machining program was broken down into steps using pseudo code that the production manager had written for our team. Using that code, we were better able to understand what was happening at each step (Appendix I). We then timed the steps with a stopwatch in both the fastest and slowest machines to observe if there were any noticeable discrepancies at certain steps. Using this method, we could determine where the slowest machine had excess time compared to the fastest machine.

3.5 Meeting with CCAT

One of the most significant steps we took in working towards a solution was going to the Connecticut Center for Advanced Technology (CCAT, 2015). CCAT is a non-profit company that partners with many manufacturing companies and education programs to help improve manufacturing processes. We were able to sit down with two CCAT representatives, Henry and John, and explain the problems with the machining process and the magnitude of the bottleneck within JAZ and discuss avenues and solutions to pursue. From our discussion we discovered some mutual connections between JAZ and CCAT with some of the milling tool manufacturers as well and Mazak.

In our meeting we discussed many possible solutions. We talked about running the second operation on an entirely different machine, although not feasible this was a good suggestion. Next we talked about making sure all the machines were running as fast as they could. CCAT gave us a lot of insight as to where time issues could be accounted for, as shown in Table 3.

Advice from CCAT
Look into tool retraction speeds and traverse speeds
Observe how tool changes are performed
Figure out if the machines know the tool offsets
How does the operator communicate with the control?
Are there defects, and what causes them?
Can look ahead acceleration and deceleration parameters be adjusted?

Table 3: CCAT Advice

From the information we had, and our ability to answer most of their questions they said the issue was most likely related to each individual CNC machine’s parameter settings. From this we were able to conclude that contacting Mazak, the machine manufacturer, and presenting the problem might be a potential solution as far as balancing the cycle times. This would assist in making the slower machines as fast as the fastest machine.

Another option that CCAT brought to light was high-speed machining. As a group we had not yet heard about this method and did not know it might be an optional solution. With high-speed machining the tool moves faster but has less of a chip load to support. As a result there would be less tool breakage and most likely a significant drop in overall cycle time as well as a fewer number of tools used in the process. CCAT told us we could contact CID, a tool manufacturer for machining, about what tools to use in making this part with the high-speed machining process. Conveniently, the CID tool representative that CCAT was in contact with was the same person JAZ speaks to from CID tools (CID, 2016).

3.6 Mazak Assistance

After meeting with CCAT, our next course of action was to get into direct contact with Mazak in order to get to the bottom of the problem regarding varying cycle times. We were provided with contact information for an account manager at Mazak who has worked with JAZ in the past. We expressed that we were an MQP group at WPI working with JAZ Manufacturing to improve their machining efficiency for one of their mass produced parts, all machined on Mazak HCN 5000 CNC's. We laid out the problem that each of the 6 machine's run cycle time were different, with some of those differences being significant, all while running the same exact program. We also included a few cycle time charts for Mazak to get a better understanding of the problem. After exchanging emails with management, Mazak offered a few suggestions, shown in Table 4.

Step 1: Provide corresponding serial numbers and machine specs for each machine to Mazak. * Variables machine to machine: * ATC type (40/60 drum type, 80/120 chain type) * Rotary type (full 4th, nc positioning, 1 degree)	**Step 2:** Take the CAM data from each machine and run the program simulation offline (Matrix CAM). * Matrix CAM will pick up differences in 'user parameters' but not 'machine parameters'. * If they all run the same, we likely have machine parameter differences.	**Step 3:** Mazak can run a 'parameter compare' - picking up variations in machine parameter settings. Mazak would need the following to test: * CAM data * Parameter data * Serial #'s on each machine.

Table 4: Mazak Suggestions

All of the suggested steps were followed, and each machine's information was loaded and transferred to a USB and mailed to Mazak headquarters.

3.7 CID Assistance

After working with CCAT, it was determined that reaching out to JAZ's specialized milling tool manufacturer would be a good idea to get a better understanding when it comes to high speed machining.

After communicating with CID representatives, we determined that high-speed milling saves time if the milling is typically more than one times the diameter, preferably more towards two times the diameter, of the tool selected (CID, 2016). Tool pressure is reduced as long as machining doesn't chip or crowd the tool, and make sure they aren't run any tighter than the two o'clock position on the tool in general. Increasing cutting speed increases chip volume. It's faster to slot if using one times the diameter of the tool or less, typically. CID has done peel milling of inconel on a Bridgeport before, and according to them, the results include a drastic reduction in heat versus slotting.

Typically tool life is shortened because the programmer doesn't push the feed rate fast enough. In layman's terms if you're looking at slotting versus peel milling on a machine, you will see massively better life peeling than slotting. However, on a very high-end machine the case may be different. If the pocket depth is say two times the diameter of the tool, high-speed machine for sure (CID, 2016).

JAZ also wants to make sure to set up the machine program with a constant percentage of tool diameter. Typically, CID will use 6% to 10% of the diameter as the step over per pass. It also needs to be remembered that even though you may program at a fast feed rate, the machine may never achieve that rate, especially on tight turns and short straight sections.

Chapter 4: Results and Financial Analysis

4.1 Cycle Time Results

After analyzing the average cycles time of the machines, it was obvious that there were large discrepancies between JAZ's CNC machines. The machine with the fastest cycle time was Machine 8, and the slowest was Machine 4. The total time difference between these machines is 29 minutes, shown in Table 2. If all the cycle times were equalized to meet that of the fastest machine, JAZ would save both time and money.

JAZ needs to produce 100,000 pieces per month. Assume there are 24 hours of labor per day Assume there are 30 days in a month Each cycle produces 80 parts
100,000 pieces needed per month / 80 pieces per cycle = 1250 total cycles needed per month
1250 cycles per month / 6 total machines = 208.33 cycles per machine per month
208.33 cycles per machine per month / 30 days = 6.94 cycles per machine per day
24 hours per day / 6.94 cycles per machine per day = 3 hour, 27 minute cycle time needed

Table 5: Cycle Time Calculations

Using the assumptions and calculations above, not all of the machines at JAZ are meeting the cycle times needed in order to produce 100,000 pieces per day. Thus, they are not producing at takt. Half of the machines are just meeting the cycle time requirements, but the other 3 machines are not. The desired cycle time of 3 hours and 27 minutes is also assuming that nothing goes wrong with the machines and there is no downtime, and does not take into consideration when the operations must to tool changes. Therefore, even though some machines are running under that time, it still may not be fast enough when other variables are taken into account. The slower machines will slow down the entire process and now allow JAZ to meet customer demand rate and therefore the cycle times must be reduced.

4.2 Machining Step Results

The next step was to determine why the machining process ran at different times, and which steps these time differences were affected. This information was obtained through timing each step of the fastest and slowest machines. The biggest difference was PLD SubPocket units 3-4 step, with the slowest machine at 3 minutes and 41 seconds, and the fastest at 3 minutes and 8 seconds. This one step gets repeated 9 times on each pallet, and there are 2 pallets that get operated on per cycle, as shown in Table 6.

	Machine 4 (Slowest) Time in Seconds	**Machine 8 (Fastest) Time in Seconds**	**Fastest-Slowest (Seconds)**	*** number of repetitions (Seconds)**	*** 2 pallets per cycle (Seconds)**
PLD SUBPOCKET (9 repetitions)					
Unit 1	136	137			
Unit 2	159	158	1	9	18
Unit 3-4	221	188	33	297	594
60 PLD SUBROUGH (3 repetitions)					
Unit 1-2	106	102	4	12	24
Unit 3-5	53	65			
60 PLD RAILS (3 repetitions)					
Unit 1-2	31	26	5	15	30
60 PLD SUBFINISH (9 repetitions)					
Unit 1	78	76	2	18	36
Unit 2	27	28			
Unit 3	44	42	2	18	36
Unit 4	25	24	1	9	18
Unit 5	34	33	1	9	18
Unit 6	68	68			
Unit 7-11	168	163	5	45	90
Unit 12	64	62	2	18	36
Unit 13	29	29			
				Total Seconds Saved	**900**

Table 6: Time Saved if Cycle Times Equalized

In order to determine how many seconds could be saved by bringing the slowest machine up to speed with the fastest machine, we calculated how many seconds per step would be saved. This accounted for how many times a specific step was repeated, and accounted for 2 pallets for cycle. After the calculations, we found that 900 seconds (15 minutes) could be saved if the slowest machine ran its operations identical to the fastest machine. By matching the machining step times of Machine 4 to Machine 8, JAZ would save $22.50 per cycle, shown in Table 7.

Machining rate = $90.00/hr = $1.50/minute
15 minutes * $1.50/minute = $22.50 saved per cycle
$22.50 saved per cycle * 208.33 cycles per machine per month = $4,687 saved per month
$4,687 saved per month * 12 months per year = **$56,244 saved per year**

Table 7: Money Saved by Equalizing One Machine's Cycle Time

The above calculations show that the 15 minute discrepancy that we recorded could save JAZ $56,244 per year if the time difference were removed. This total savings calculated for only that one machine. There are another 5 machines that would also save JAZ more money if their cycle times were reduced.

Even though there were some time differences between the steps in the different machines, the differences are not large enough to account for the total cycle time difference of 29 minutes between Machine 4 and Machine 8. From this we can conclude that there could be a parameter setting difference on the machines that could be causing the variance.

If we were accounting for the full 29 minute discrepancy between the fastest and slowest machine, then JAZ would save $43.50 per cycle by reducing the cycle time of Machine 4.

Machine Number	Average Cycle Time	Minutes Saved if Cycle Time Equalized to MH-8	Money Saved if Cycle Time Equalized to MH-8	Money Saved per Month (208.33 cycles per machine per month)
MH-2	**3** hours, **28** minutes	17 minutes	$25.50 per cycle	$5312
MH-3	**3** hours, **15** minutes	4 minutes	$6 per cycle	$1250
MH-4	**3** hours, **40** minutes	29 minutes	$43.50 per cycle	$9062
MH-8	**3** hours, **11** minutes	0 minutes	$0 per cycle	$0
MH-9	**3** hours, **29** minutes	18 minutes	$27 per cycle	$5625
MH-10	**3** hours, **14** minutes	3 minutes	$4.5 per cycle	$937
Total Money Saved per Month				$22,186
Total Money Saved per Year				$266,232

Table 8: Money Saved if All Cycle Times Equalized

JAZ Manufacturing would save a total of $266,232 per year if the cycle times of all 6 machines were equalized to be 3 hours and 11 minutes, as shown in Table 8 and Figure 11. An investment of $10,000 is estimated in order to balance the cycle time. A breakdown of this investment is shown in Table 9.

Fully loaded shop rate of $90/hour
Machine down time 20 hours at $90/hour = $1800
Hiring outside help for parameter compare = $5700
Quality assurance verification of new program = $1500
Reload CNC program settings = $1000
Total Estimated Investment = $10,000

Table 9: Investment Breakdown Balancing Cycle Times

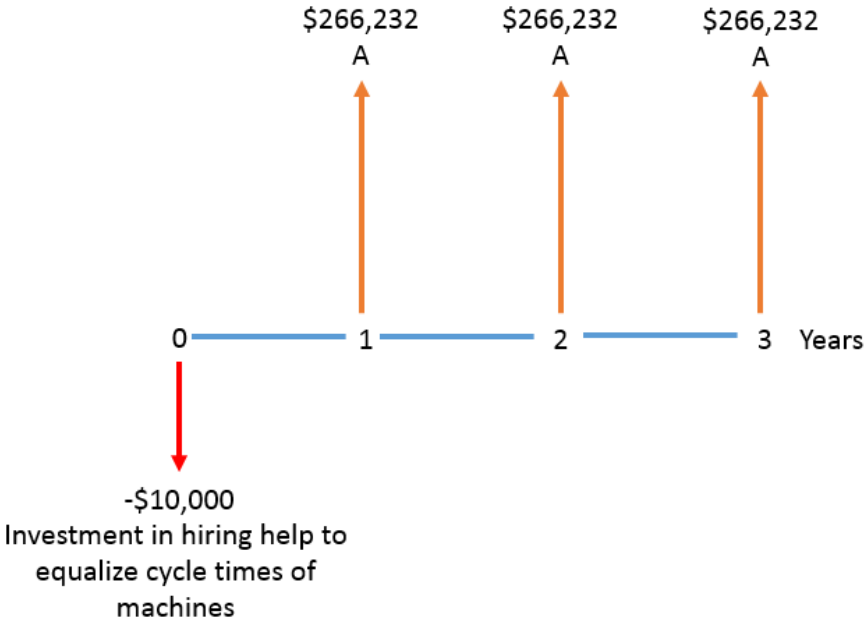


Figure 11: Cash Flow Diagram for Equalizing Cycle Times

Assumptions: JAZ invests $10,000 to balance their cycle times, i = 8%, n = 3

$$P = A\ (P/A, i, n)$$

$$=\$266{,}232\ (P/A, 8\%, 3)$$

$$= \$266{,}232\ (2.5771)$$

$$= \$686{,}106$$

$$\$686{,}106 - \$10{,}000 \text{ initial investment} = \$676{,}106$$

4.3 Parameter Comparison

After speaking with an applications engineer at Mazak, we found some answers as to why cycle times were so different between the two machines. Mazak created both the slowest and fastest machines in a program called Matrixcam and ran some test cycles finding the following conclusions.

First, one machine has a 12K spindle and the other has an 18K. JAZ makes all of its programs in Mazatrol which does everything in surface feed per minute (SFM) for the spindle speed and inches per revolution for the feed rate. Because the one machine has a faster spindle, running it faster will speed up the feed and reduce the cycle time. The 12K spindle machine will only run up to 12K no matter how fast the SFM in the program is telling it to go. So if the SFM is telling it to go faster, it will on the 18K machine and speed up the feed as well. Mazak also stated the actual RPM must be within 20% of what the SFM is calculating or the machine will indicate an alarm so this is where an effect in cycle time could be hidden.

Next, Mazak deleted all the programs from one of the machines and copied all the programs over from the other to make sure both were exactly the same. The main program names were different from the outset and running a tool path check after copying the program changed the cycle time which tells us that the programs in the two machines were not identical.

The potential issue was the user parameter settings not being identical. To test this, the user parameters from one machine to the other were copied, which did not seem to have any effect on the cycle time. It is okay to copy the user parameters from one machine to another as long as they have the same control, since they are not machine specific. However, you cannot copy the machine parameters from one machine to another as they are machine specific. It was also suggested that JAZ should back-up all the user parameters somewhere off the machine.

Moving forward, the maximum rapid traverse speed parameter in both controls were checked and they were the same. Finally, Mazak did a parameter comparison check of both the user and machine parameters and found nothing that would cause a significant cycle time difference. By editing the maximum RPM in the tool field and making them all the same and copying the user parameters, he was able to make the cycle times identical. However, Mazak also said JAZ is not taking advantage of how fast the machines are able to go.

4.4 High Speed Machining

When meeting with CCAT, one suggestion that was made was to try high speed machining. The benefits of high speed machining are that is could reduce cycle time, create more accurate pieces, and has a high material removal rate. In high speed machining, there is a low cutting force, and both the cutting tool and workpiece are kept at a low temperature. The low cutting force can help to reduce the tool wear.

High speed is defined as a rotational spindle speed between the range of 15,000 and 25,000 rpm. The high speed cutting range is between 914 - 1,524 ft/min (279 - 465 m/min) in non-ferrous applications. When applied to steel, the cutting speed is 305 - 366 ft/min (93 - 112 m/min) (Erdel, 2003). With increased cutting speeds, chip volume and surface quality increase, but the cutting-tool life may be shortened. The cutting forces decrease and less heat is generated. This is ideal for thin walled pieces. Tool life can be prolonged with advanced cutting-tool material.

The benefits of high-speed machining far outweigh the cost for the initial investment because the metal removal rate increases three fold, there can be up to 70% reduction in machining time, and the cost of machining decreases 25-50% (Davim 2015). Another benefit of high speed machining is the quality of surface finish. Currently, JAZ puts all the pieces into a tumbler which takes 90 minutes. With high speed machining, the tumbling would no longer be required, which could mean major savings in both time and money.

In conventional machining, even a relatively small slot, such as one about 20 mm wide, might have traditionally required three or four passes. High speed machining can save time by removing the material in one continuous pass. Today, machines and cutting tools can do much more than ever before. They are capable of much higher spindle speeds and feed rates. In order to take full advantage of their capabilities, smaller tools have been developed to perform a multiple number of operations in a single job setup, including, but not limited to, square shoulder milling, contouring, plunging, slotting and both helical and circular interpolation. These tools allow their users to embrace new methodologies. One effective method of high speed machining is peel milling, which offers a way for shops to overcome challenged that slotting in difficult materials presents (Trent 2000).

Peel milling is not considered to be a new process, however the modern application of it is consider to be. In the past, peel milling was only used for either a finishing or roughing pass. Doing both of those operations required two tools because of limitations in both the machine and tooling. Advancements in today's world have allowed for peel milling to perform a roughing and finishing pass to occur at the same time. Peel milling involves a high axial depth of cut, sometimes up to the cutting maximum, combined with a very small radial engagement of five to ten percent of the tool diameter. The combination results in a decrease in cutting forces, specifically radial forces. Due to this, both feed rate and speed can be increased. This in turn results in many benefits for users, including greater stability, faster metal removal and more precise machining. Another benefit of peel milling is that it potentially eliminates secondary operations due to the small radial engagement and low cutting forces that produce a very precise and smooth finish. Low cutting forces can also lead to a longer and more predictable tool life. Reduced radial contact between both the workpiece and the tool contribute to prolonged tool life. This is because the tool has less time to heat up with more time to cool down with each revolution. This additional tool life is significant when one considers that a tool used during peel milling can also perform a variety of additional machining operations. This can lead to the elimination of many tools in a single set up (Schultz, 1992).

One type of peel milling that would be beneficial to JAZ would be the trochoidal method. This uses a series of overlapping circular cutting paths in the X and Y direction with no machine rest to machine a slot at full depth. This method was first developed to address the heightened demands of hardened and difficult materials. Though the radial engagement in this method is relatively low, the cutter will still be fully engaged and can be subject to vibration and deflection. Only rigid and strong cutter bodies can be used with stable process conditions. Another requirement is a tool with free cutting geometry. Some inserted end mills provide these features in relatively small tool diameters, and a single tool can produce a slot ranging from slightly bigger than its own diameter and up to several times its diameter. Like JAZ is currently doing, removing material from a cavity or pocket using slower speeds with numerous passes is very time consuming. With what used to be a very slow process that was only accomplished with more expensive solid carbide end mills, can now be accomplished in much less time with much better results using indexables. With Trochoidal peel milling methodology, operators can follow the contour of the part with an increased cutting data, resulting in a dramatically reduced number of passes and reduced overall machine cycle time. It is almost guaranteed that if JAZ were to use this methodology, their cycle time would be significantly reduced. (Schultz 2004)

Many articles have concluded that high speed machining leads to the minimization of machining process cost, along with energy consumption. One specifically put forward a direct relationship between process cost and energy consumption. A machining cost model was developed regarded tool wear and energy consumption (Anderberg, 2010). The direct energy that was required for material removal was minute compared to the energy that was demanded by the equipment modules. With that, process cost and energy consumption models were developed in terms of the drilling process parameters. The author had claimed a 13.5 percent reduction in energy consumption and a 22 percent increase in tool life after optimizing those parameters (Diaz, 2011).

Another report was conducted to determine the difference between conventional machining and high speed machining regarding sustainability. The results of the work were that the cutting mode is highly influential on the sustainability of the metal cutting process. The effects on all the tested measures including tool life, productivity, specific energy consumption, and process cost were significantly high. The analysis founds that high speed machining is the obvious choice for enhanced productive and reduction of energy consumption. (Al-Ghamdi, 2015)

4.5 High Speed Machining Financial Analysis

Due to our research and speaking to professionals in the field, we believe that JAZ would immensely benefit from machining these FBAR packages through high speed machining methodology. The benefits of high speed machining would potentially far outweigh the cost for the initial investment. Amongst these benefits are two that would greatly add value to the overall process. There is potentially a huge reduction in machining time, and a potential decrease in the cost of consumable tools.

We can confidently assume that high speed machining the FBAR packages will result in a significant decrease in cycle time. To explain why high speed machining would be a beneficial investment to JAZ, let us assume a 20 percent reduction in machining cycle time (Table 10).

After equalizing cycle times, all the cycle times are 3 hours, 11 minutes (191 minutes)
Assume a 20% reduction in cycle time
191 minutes * 0.20 = 38.2 minutes
New cycle time = 191 minutes – 38.2 minutes = 152.8 minutes

Table 10: Reduced Cycle Time Calculation

Switching to high speed machining would save 38.2 minutes each cycle. The new cycle time for high speed machining would be about 153 minutes.

Machining rate = $90.00/hr = $1.50/minute
38.2 minutes * $1.50/minute = $57.30 saved per cycle
Assume the machines are running 24 hours per day
(24 hours/day * 60 mins/hour) / 153 mins cycle time = 9.4 cycles per machine per day
Now, each machine is capable of running 9.4 cycles per day
9.4 cycles per day per machine * 6 machines * 30 days/month = 1692 cycles per month
1692 cycles/month * 80 pieces/cycle = 135,360 pieces per month
JAZ would be able to machine 135,360 parts per month with high speed machining
This is about 35,360 more pieces per month than JAZ currently makes 35,360 per month * 12 months/year = 424,320 pieces/year

Table 11: High Speed Throughput Calculation

As shown in Table 11, each year 424,320 more pieces would be produced, thus potentially eliminating the bottleneck of the machining process. Currently JAZ produces 100,000 pieces each month. With an additional 424,320 pieces per year, that is equivalent to more than an additional 4 full months of operation (or one-third of an entire year). In one year, the FBAR yield would increase by 35% (Table 12).

Current state:	**High speed implemented:**	**Percent change per year:**
100,000 pieces/month * 12 months/year = 1,200,000 pieces per year	1,200,000 current pieces/year + 424,320 additional pieces = 1,624,320 pieces per year	(1,624,320 / 1,200,000) = 1.35 = 35% increase

Table 12: Yield Increase of High Speed Machining

Assume they still only run 7 cycles per day to produce 100,000 pieces per month
$57.30 saved per cycle * 7 cycles per day * 6 machines = $2406.60 saved per day
$2406.60 saved per day * 30 days = $72,198 saved per month
$72,198 saved per month * 12 months per year = $866,376 saved per year

Table 13: Yearly Savings of High Speed (7 cycles per day)

If JAZ were to continue running at the same throughput of 100,00 pieces per month, then their machines would not have to run as often. This would mean more machine downtime, which is a waste, but a savings in money for machining time. In total, the savings would be $866,376 per year if they still only ran 7 daily cycles for each machine (Table 13).

However, with the reduced cycle time JAZ can run each machine at 9.4 cycles per day, which would be a total savings of $1,163,419 per year (Table 14).

Now assume JAZ runs the full 9.4 cycles per day
$57.30 saved per cycle * 9.4 cycles per day * 6 machines = $3231.72 saved per day
$3231.72 saved per day * 30 days = $96951.60 saved per month
$96951.69 saved per month * 12 months per year = $1,163,419 saved per year

Table 14: Yearly Savings of High Speed (9.4 cycles per day)

From all the calculations, we recommend that JAZ move forward with implementing high speed machining as it would have a huge pay off. An estimated $20,000 should be invested into high speed machining, which is broken down in Table 15.

Fully loaded shop rate of $90/hour
Hiring outside experts = $7000
Reprogram FBAR tool path 50 hours at $90/hour = $4500
New tools = $2000
Running tests and quality assurance = $5000
Reload CNC program settings = $1500
Total Estimated Investment = $20,000

Table 15: Investment Breakdown High Speed

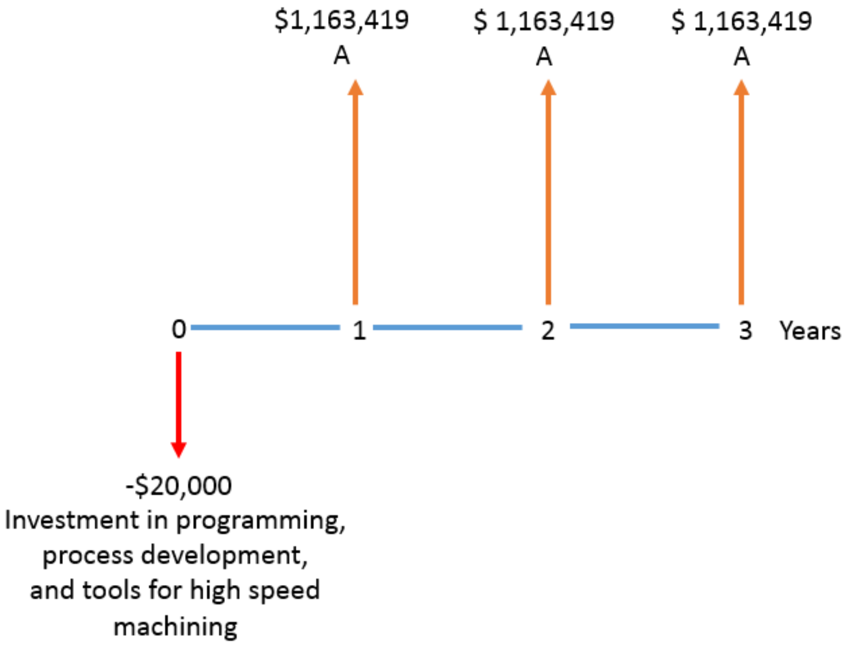


Figure 12: High Speed Cash Flow Diagram

Assumptions: JAZ spends $20,000 to implement high speed machining, i = 8%, n = 3

P = A (P/A, i, n)

=$1,163,419 (P/A, 8%, 3)

= $1,163,419 (2.5771)

= $2,998,247

$2,998,247 - $20,000 initial investment = $2,978,247

It must be noted that although the initial investment is $20,000, it would be significantly less of an investment to determine if high speed machining will be worthwhile. The $20,000 investment would be for the full switch to high speed methodology once it has been determined worthwhile.

4.6 Tool Life Analysis

Tool wear can be described as the failure of cutting tools over time due to regular operation of the tools. There are several types of tool wear that can occur, such as flank wear and crater wear. Flank wear occurs when the part of that tool that is in contact with the finished part begins to erode, and this can be described by Taylor's tool life equation. Crater wear is a normal type of tool wear that happens when contact with the chips erodes the rake face. This only becomes a big issue when it causes a cutting edge failure.

There are many factors to take into consideration when determining tool life which are cutting tool material, cutting tool geometry, machine condition, cutting tool clamping, cutting speed, feed, and depth of cut. When considering an economic tool life approach, the costs of the operations would be at the lowest. Using a productivity tool life approach, the only factor to consider would be how productive the tool is overall, regardless of the cost of the operation.

Taylor's Tool Life Equation can be applied to determine the life expectancy of a given tool (Schey, 2000).

A general form of the equation is as follows:

$$\mathbf{V_c\,T^n = C}$$

$\mathbf{V_c}$ = Cutting Speed (m/min)

$\mathbf{T}$ = Tool Life (min)

$\mathbf{n}$ and $\mathbf{C}$ are constants determined by the properties of the tool, workpiece, and feed rate.

Work Material	Tool Material	n
Steel	Carbide Coated	0.4 – 0.6
Steel	High Speed Steel	0.08 – 0.1
Steel	Cemented Carbides	0.25 – 0.4

Table 16: n Constants for Tool Life

. JAZ Manufacturing have determined their tool life based upon experimentation and observing when the tools break. Then, they created a system such that each tool gets changed out before it reaches that breaking point. The current system that they use is not optimized. For example, they might change out some tools early that could last another entire cycle or two. Most of the tools get replaced after 5 cycles. If one of the tools could last 6 cycles, it still gets replaced after 5 because it’s easier for the operators to change out all the tools at once than to change only one tool at a time in between cycles. What this means is that if 10 tools get changed every 5 cycles, that’s easier to handle than 7 tools getting changed every 5 cycles, 1 tool change every 6 cycles, and 2 tool changes every 3 cycles. Although this may be more convenient for the operators, JAZ may not be getting the tools’ full potential, and therefore not getting the most value out of the tools that they purchase.

To machine the FBAR, JAZ Manufacturing uses 13 tools (Appendix G). The different tool materials are carbide coated, carbide, and high speed steel. To determine if JAZ is optimizing their tools, Taylor’s tool life can be applied. The 6 tools that are carbide coated will be analyzed, and the first step is to calculate how long each of the tool is cutting for during one cycle. A summary of this information is shown below. All the calculations to determine these numbers can be found in Appendix J.

CARBIDE COATED TOOLS					
Tool #	Speed (sfm)	Speed (m/min)	# Cycles before tool change	Cutting Time of 1 Cycle	Tool life used by JAZ = Cutting Time of 1 cycle * # cycles before tool change
2	**575**	**175.3**	**5 cycles**	**51.4 min**	**257 minutes**
3	**750**	**228.6**	**5 cycles**	**90.4 min**	**452 minutes**
4	**750**	**228.6**	**5 cycles**	**43.8 min**	**219 minutes**
6	**500**	**152.4**	**5 cycles**	**16.3 min**	**81.5 minutes**
8	**700**	**213.4**	**5 cycles**	**56.4 min**	**282 minutes**
15	**300**	**91.4**	**15 cycles**	**48.9 min**	**733.5 minutes**

Table 17: Carbide Coated Tool Life Calculations Used by JAZ

For carbide coated, assume n = 0.5 (Table 16).

For this analysis, we will assume that one of the tools has the correct tool life in order to determine the constant C. Tool 8 will be assumed to have the correct tool life of 282 minutes.

Tool 8

$$\mathbf{V_c\, T^n = C}$$

Given: $V_c = 213.4$ m/min, T = 282 mins

$$213.4 * 282^{.5} = C$$

$$3583.6 = C$$

Now both constants n and C are defined and tool life calculations can be performed for the other carbide coated tools.

Tool 2	Tool 3	Tool 4	Tool 6	Tool 15
$\mathbf{V_c\, T^n = C}$ $175.3 * T^{.5} = 3584$ $T^{.5} = 20.44$ $.5 \log T = \log 20.44$ $\log T = 2.62$ $T = 417$ min	$\mathbf{V_c\, T^n = C}$ $228.6 * T^{.5} = 3584$ $T^{.5} = 15.68$ $.5 \log T = \log 15.68$ $\log T = 2.40$ $T = 251$min	$\mathbf{V_c\, T^n = C}$ $228.6 * T^{.5} = 3584$ $T^{.5} = 15.68$ $.5 \log T = \log 15.68$ $\log T = 2.40$ $T = 251$min	$\mathbf{V_c\, T^n = C}$ $152.4 * T^{.5} = 3584$ $T^{.5} = 23.52$ $.5 \log T = \log 23.52$ $\log T = 2.74$ $T = 550$ min	$\mathbf{V_c\, T^n = C}$ $91.4 * T^{.5} = 3584$ $T^{.5} = 39.21$ $.5 \log T = \log 39.21$ $\log T = 3.18$ $T = 1513$ min

Table 18: Tool Life Prediction Calculations

As shown in Table 18, the calculated tool life of each tool can be compared to the tool life of tool 8, which we assumed was perfectly correct and will use as a control. Both tools 3 and

4 have a predicted tool life of about 251 minutes, which is relatively close to the tool life of tool 8 (282 mins). From that we can conclude that tools 3 and 4 should be changed at the same time of tool 8, every 5 cycles, which they currently are. Tool 2 has a predicted tool life of 417 mins, about 1.5 times that of tool 8. Therefore, tool 4 is able to last longer than tool 8. It should not be changed out every 5 cycles, because it could last 7 or 8 cycles before it breaks. The predicted tool life of tool 6 is 550 minutes, almost twice as long as tool 8. This mean that tool 6 also should not be changed every 5 cycles, but instead every 10 cycles. Lastly, tool 15 has a predicted tool life of 1513 minutes, which is more than 5 times the tool life of tool 8. Therefore tool 8 and tool 15 should not be changed out at the same time, which they currently are not. JAZ currently changed tool 15 every 15 cycles, and according to the calculations it could potentially last 25 cycles.

In conclusion of this analysis, JAZ has not optimized their tool changes. Tools get replaced before they need to be. JAZ could save money if they did not replace the tools until they have nearly reached the end of their life.

Chapter 5: Conclusion

Moving forward, as shown through research and financial analysis, it would be in JAZ's best interest to make a few changes to their FBAR machining process. In order to run their current machining process as efficiently as possible, JAZ should balance the cycle times across all their CNC machines by optimizing their machine parameter settings, as well as optimize their cutting tool life. In order to balance the CNC machine cycle times, it is recommended that Mazak is brought on site to assist with the parameter settings issue. Additionally, we also recommend that JAZ apply the high speed peeling methodology when machining the FBAR. We recommend that JAZ further investigate high speed methodology to determine the best application for their machining process.

The objective of this MQP was to reduce non-value added time during the machining of a high volume part for the project sponsor JAZ Manufacturing. Direct observation and measurement of the machining process was performed to gain understanding and determine any problems. The methods used included value stream mapping, axiomatic design, Taylor's tool life equation and engineering economic analysis. Decomposing the functional requirement of machining the part showed that a significant reduction in machining time was possible. The conclusion shows that an analysis of non-value added time, along with the application of the best practices in machining can yield a large reduction in processing time, increased productivity, and substantial savings for the company.

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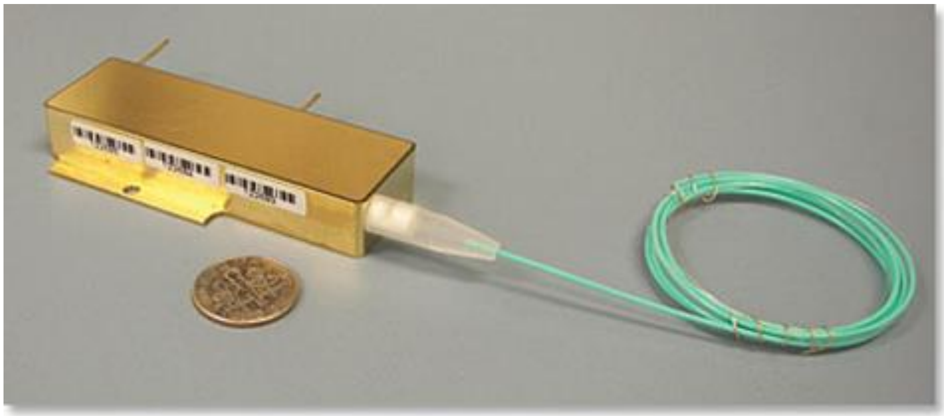
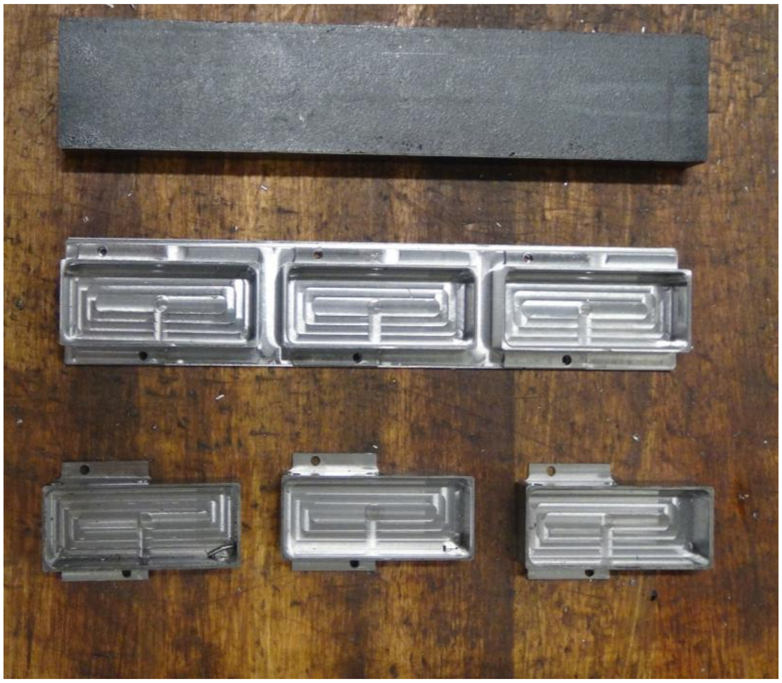
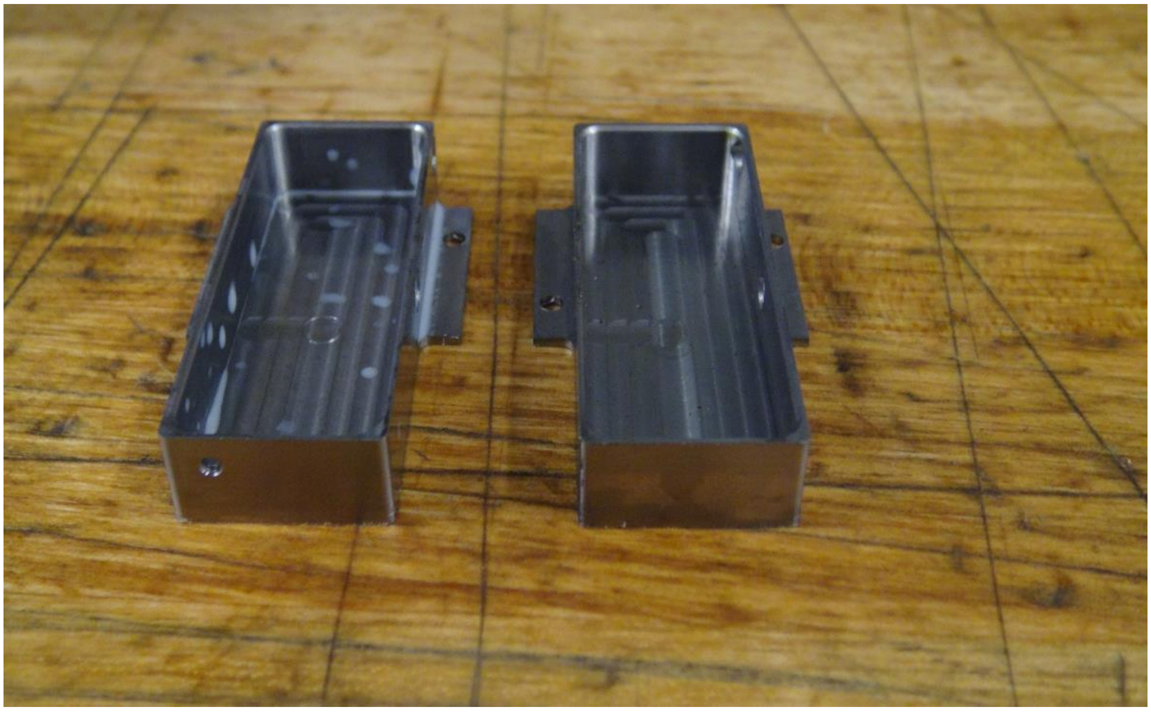
Appendix A: Completed FBAR Package

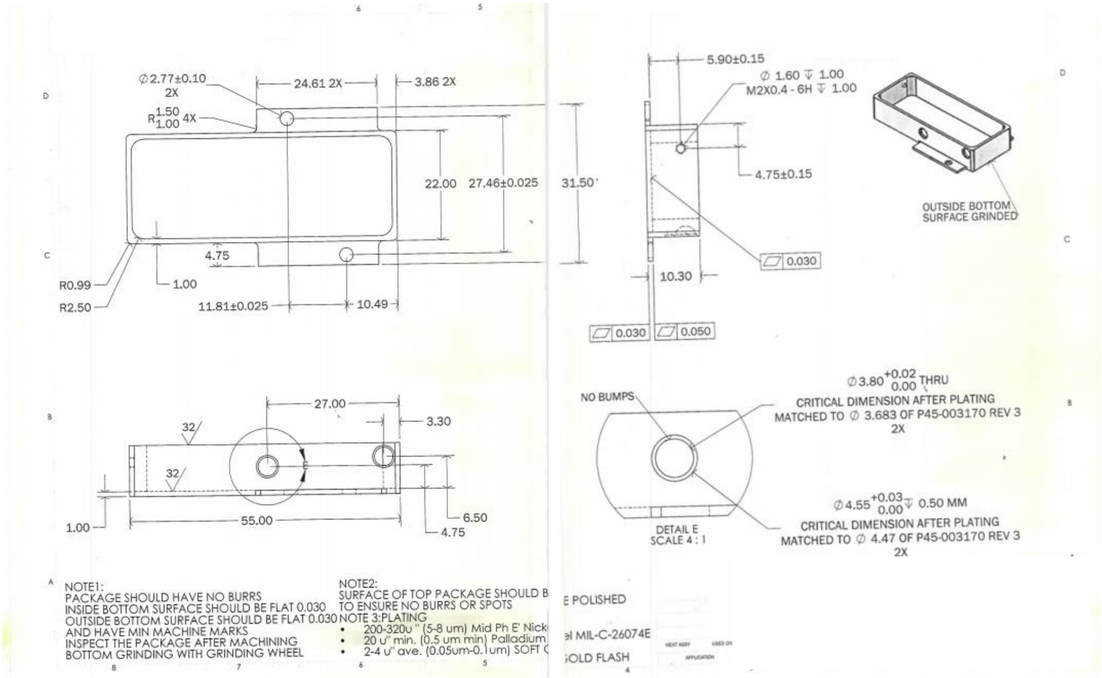


Appendix B: FBAR Raw Material to Finished Machined Part

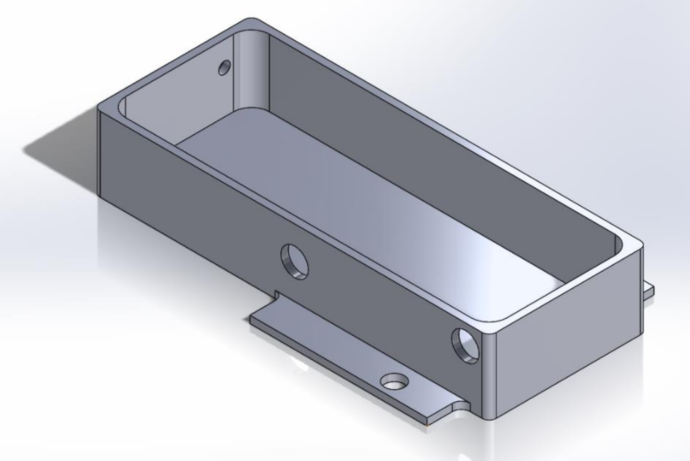




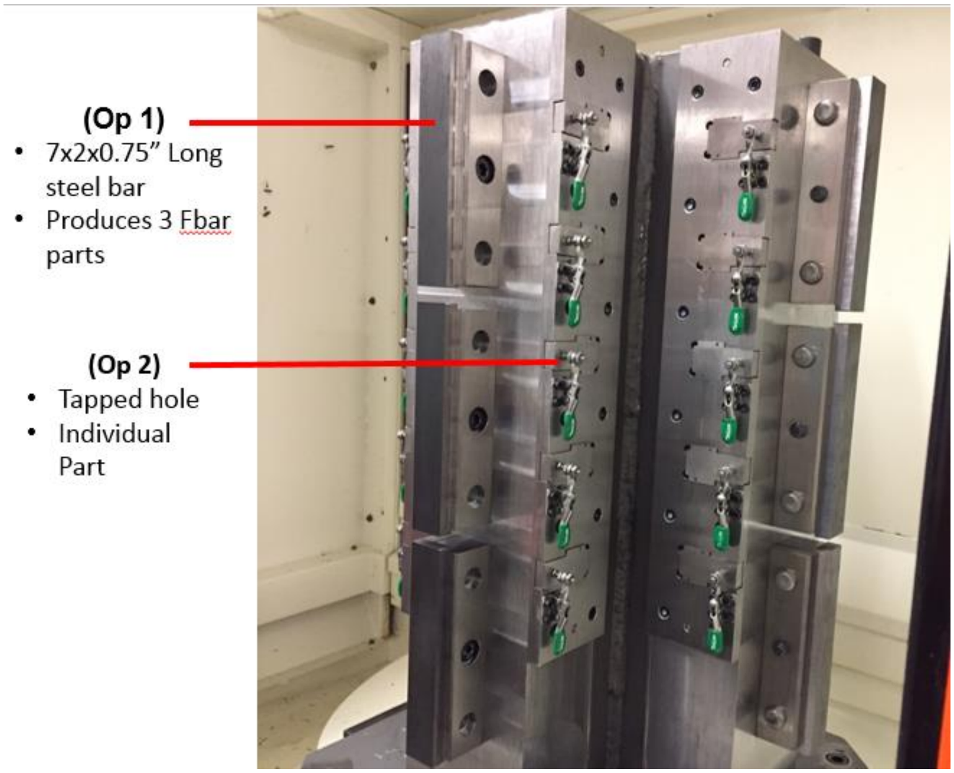
Appendix C: FBAR Blueprint



Appendix D: FBAR CAD



Appendix E: Mazak Machine Photos



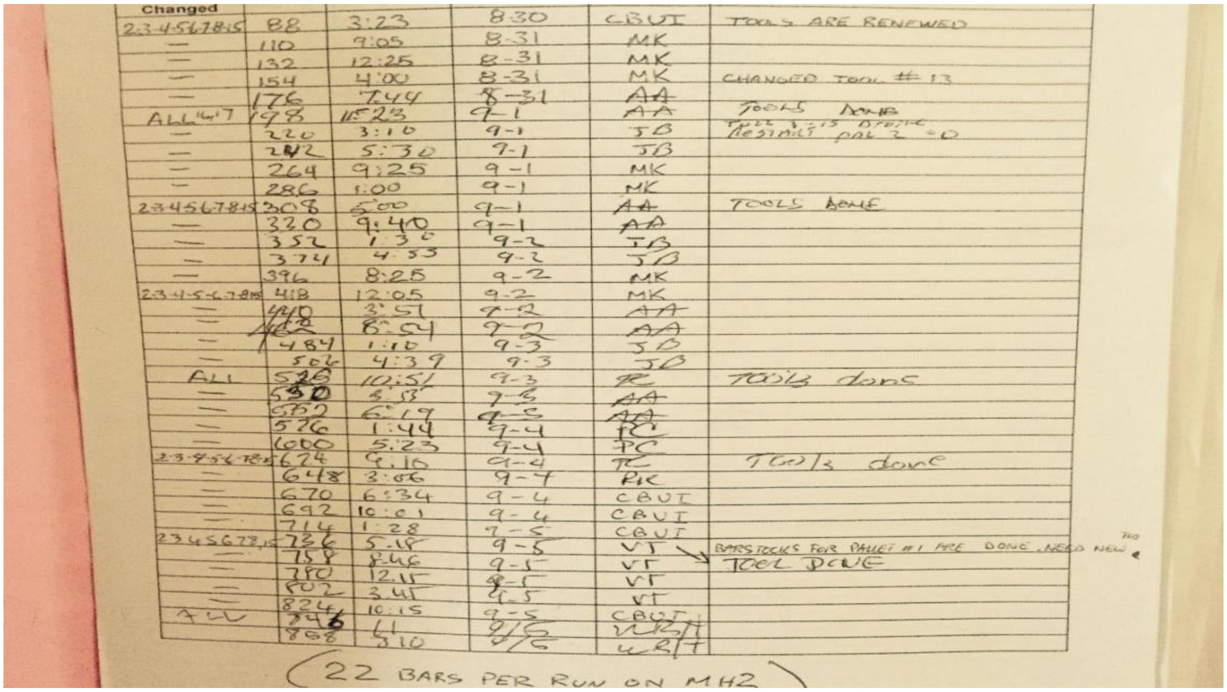
(Op 1)

- 7x2x0.75” Long steel bar
- Produces 3 Fbar parts

(Op 2)

- Tapped hole
- Individual Part

Appendix F: Example of Tool Change Log



Changed					
2-3-4-5-6-7-8-15	88	3:23	8-30	CBUI	TOOLS ARE RENEWED
—	110	9:05	8-31	MK	
—	132	12:25	8-31	MK	
—	154	4:00	8-31	MK	CHANGED TOOL # 13
—	176	7:44	8-31	AA	
ALL "4"7	198	11:23	9-1	AA	TOOLS DONE
—	220	3:10	9-1	JB	TOOL 3-15 BROKE RESTART PAL 2 [illegible]
—	242	5:30	9-1	JB	
—	264	9:25	9-1	MK	
—	286	1:00	9-1	MK	
2-3-4-5-6-7-8-15	308	5:00	9-1	AA	TOOLS DONE
—	330	9:40	9-1	AA	
—	352	1:30	9-2	JB	
—	374	4:55	9-2	JB	
—	396	8:25	9-2	MK	
2-3-4-5-6-7-8-15	418	12:05	9-2	MK	
—	440	3:51	9-2	AA	
—	462	8:54	9-2	AA	
—	484	1:10	9-3	JB	
—	506	4:39	9-3	JB	
ALL	528	10:51	9-3	PC	TOOLS done
—	550	3:53	9-3	AA	
—	552	6:19	9-3	AA	
—	576	1:44	9-4	PC	
—	600	5:23	9-4	PC	
2-3-4-5-6-7-8-15	624	9:10	9-4	PC	TOOLS done
—	648	3:06	9-4	RK	
—	670	6:34	9-4	CBUI	
—	692	10:01	9-4	CBUI	
—	714	1:28	9-5	CBUI	
2345678,15	736	5:18	9-5	VT	BARSTOCKS FOR PALLET #1 ARE DONE. NEED NEW TOO
—	758	8:46	9-5	VT	TOOL DONE
—	780	12:15	9-5	VT	
—	802	3:45	9-5	VT	
—	824	10:15	9-5	CBUI	
ALL	846	11	9/6	VKB	
	868	3:10	9/6	WR	

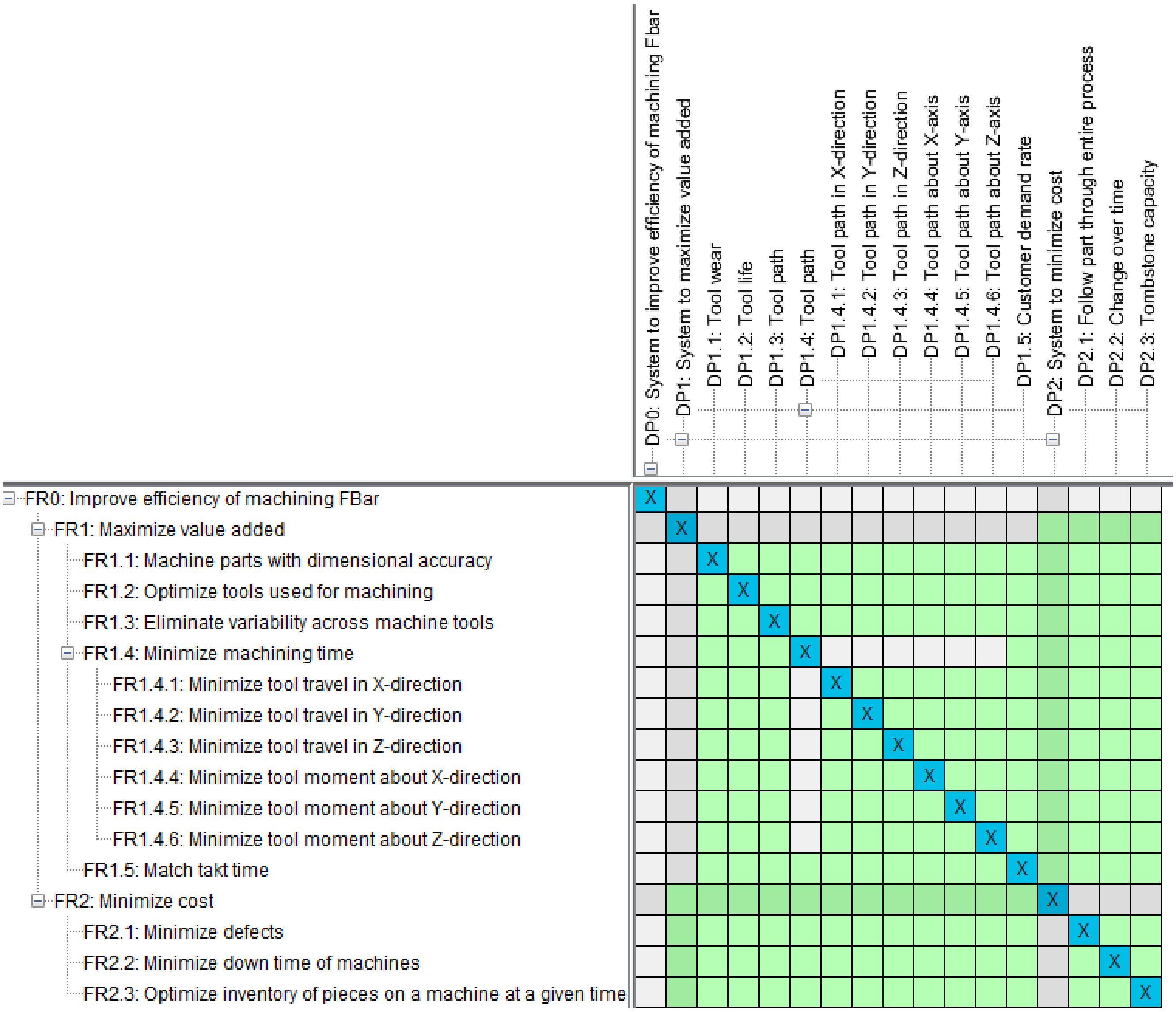
(22 BARS PER RUN ON MH2)

Appendix G: Tooling Information

Tool #	Brand	Description	Material	Number of Flutes	Function	Tool Life (# of cycles)	Speed (SFM)
2*	CID	(.31P) 5/16 End Mill .03CR	carbide coated	4	Pocket mill, rough cut after drill, line-out	5	550 - 600
3*	CID	(.25E) 1/4 End Mill	carbide coated	5	Line left, .406 deep,ghost, line-out, rim cut at 0	5	750
4*	CID	(.25F) 1/4 End Mill	carbide coated	5	Line left, .366 deep, above wings, below wings	5	750
5	SandVik	(.75P) Insert Drill	carbide insert	1	Drill, SandVik insert, beginning of pocket	5	500
6	Garr	(.25R) 1/4 End Mill (#27560)	carbide coated	4	line left, .395 deep, .2 peck, .41 deep,	5	500
7	OSG	(.11P) 2.75 MM Drill	Hi speed steel	2	Drill	5	
8*	CID	(.18P) 3/16 End Mill	carbide coated	5	Line in, finish pocket wall, finish pocket bottom	5	700
11	MA Ford	(.15P) .151 Drill	carbide	2		15	
12	Garr	(.18P) As Drill (.182 End Mill)	carbide	4		15	
13	Garr	(.12P) 1/8 Center Drill	carbide	2	Chamfer inner rim, M2 tapping cycle drill	15	100 Tapping
15	Garr	(.12P) 3 MM End Mill	carbide coated	4	Line left, picks out radius	15	300
16	OSG	(.06P) 1.6 MM Drill	hi spped steel	2	M2 tapping cycle, drill	15	104
17	OSG	(M.2P) M2 X 0.4 Tap	Hi speed steel	cut tap	M2 tapping cycle, tap	15	40

Appendix H: Axiomatic Design Coupling Matrix

#	[FR] Functional Requirements	[DP] Design Parameters
0	Improve efficiency of machining FBar	System to improve efficiency of machining Fbar
1	Maximize value added	System to maximize value added
2	Minimize cost	System to minimize cost



	DP0: System to improve efficiency of machining Fbar	DP1: System to maximize value added	DP1.1: Tool wear	DP1.2: Tool life	DP1.3: Tool path	DP1.4: Tool path	DP1.4.1: Tool path in X-direction	DP1.4.2: Tool path in Y-direction	DP1.4.3: Tool path in Z-direction	DP1.4.4: Tool path about X-axis	DP1.4.5: Tool path about Y-axis	DP1.4.6: Tool path about Z-axis	DP1.5: Customer demand rate	DP2: System to minimize cost	DP2.1: Follow part through entire process	DP2.2: Change over time	DP2.3: Tombstone capacity
FR0: Improve efficiency of machining FBar	X																
FR1: Maximize value added		X															
FR1.1: Machine parts with dimensional accuracy			X														
FR1.2: Optimize tools used for machining				X													
FR1.3: Eliminate variability across machine tools					X												
FR1.4: Minimize machining time						X											
FR1.4.1: Minimize tool travel in X-direction							X										
FR1.4.2: Minimize tool travel in Y-direction								X									
FR1.4.3: Minimize tool travel in Z-direction									X								
FR1.4.4: Minimize tool moment about X-direction										X							
FR1.4.5: Minimize tool moment about Y-direction											X						
FR1.4.6: Minimize tool moment about Z-direction												X					
FR1.5: Match takt time													X				
FR2: Minimize cost														X			
FR2.1: Minimize defects															X		
FR2.2: Minimize down time of machines																X	
FR2.3: Optimize inventory of pieces on a machine at a given time																	X

Appendix I: Program Code

60PLD2Pallets (main program Top tier, controls all subs and pallet changes)

60SNOUTMAINP1 (TIER 2, controls offsets for deviation from pallet to pallet)

60SNOUTSUBLP1 (LEFT SIDE SNOUT HOLES)

- Unit 2 (M2 tapping cycle)
  T13 (.12P ctr drill) 100sfm .003 cpr (chip per revolution)
  T16 (.06P drill) 104sfm .0061 cpr
  T17 (M2P tap) 40sfm .01574 cpr (k)

60PLDMAIN (TIER 2, controls all cutting with exception of snout holes)

PLDSUBPOCKET (repeat 9)

- Unit 1 (DRILL, sandvik insert, pocket)
  T05 (.75P) no peck 500sfm .006 cpr
- Unit 2 (Pocket mill, rough cut after drill)
  T02 (.31P end mill) 600sfm .0055 cpr width .2
- Unit 3 (line in, finish pocket wall) .358 deep
  T08 (.18P end mill) 700sfm .008 cpr .2 peck
- Unit 4 (Pocket finish bottom) .366 deep
  T08 (.18P end mill) 700sfm .007 cpr width .1
- Unit 5 tool check (previous tool)

60PLDSUBROUGH (repeat 3)

- Unit 1 (Line out, .36 deep no peck)
  T02 (.31P end mill) 550sfm .006 cpr
- Unit 2 tool check (previous tool)
- Unit 3 (line left, .395 deep, .2 peck)
  T06 (.25R end mill) 500sfm .008 cpr
- Unit 4 (line left, .395 deep, .2 peck)
  T06 (.25R end mill) 500sfm .008 cpr
- Unit 5 tool check (previous tool)

60PLDRAILS

- Unit 1 (line left, .41 deep)
  T06 (.25R end mill) 600sfm .016 cpr
- Unit 2 (line left, .41 deep)
  T06 (.25R end mill) 600sfm .016 cpr

60PLDSUBFINISH (repeat 9)

- Unit 1 (line left, .366 deep)-above wings
  T04 (.25F end mill) 750sfm .006 cpr
- Unit 2 (line left, .406 deep)-below wings
  T04 (.25F end mill) 750sfm .006 cpr
- Unit 3 (line left, .406 deep)-below wings
  T04 (.25F end mill) 750sfm .006 cpr
- Unit 4 (line left, .406 deep)-ghost below wings
  T03 (.25E end mill) 750sfm .008 cpr
- Unit 5 (line left, .406 deep)-ghost below wings
  T03 (.25E end mill) 750sfm .008 cpr
- Unit 6 (line out, rim cut at zero)
  T03 (.25E end mill) 750sfm .006 cpr
- Unit 7 (line left, picks out radius)
  T15 (.12P end mill) 300sfm .002 cpr
- Unit 8 (line left, picks out radius)
  T15 (.12P end mill) 300sfm .002 cpr
- Unit 9 (line left, picks out radius)
  T15 (.12P end mill) 300sfm .002 cpr
- Unit 10 (line left, picks out radius)
  T15 (.12P end mill) 300sfm .002 cpr
- Unit 11 tool check (previous tool)
- Unit 12 (line out, .366 deep) ghost above wings
  T03 (.25E end mill) 800sfm .008 cpr
- Unit 13 (drill)
  T07 (.11P drill) 170sfm .005 cpr
- Unit 14 (chamfer in, rim)
  T13 (.12P ctr drill) 500sfm .012 cpr

Appendix J: Cutting Time Calculations

TOOL 2	# Seconds on Fastest Machine	* # repetitions	* 2 pallets
PLD SUBPOCKET Unit 1	136	136 * 9 = 1224 seconds	1224 * 2 = 2448 seconds
PLD SUBROUGH Unit 1	106	106 * 3 = 318 seconds	318 * 2 = 636 seconds

Cutting time in 1 cycle = 3084 seconds

= 51.4 mins

TOOL 3	# Seconds on Fastest Machine	* # repetitions	* 2 pallets
PLD SUBFINISH Unit 4	24	24 * 9 = 1224 seconds	1224 * 2 = 2448 seconds
PLD Subfinish unit 5	33	33 * 9 = 318 seconds	318 * 2 = 636 seconds
PLD Subfinish unit 6	68	68 * 9 = 612 seconds	612 * 2 = 1224 seconds
PLD Subfinish unit 12	62	62 * 9 = 558 seconds	558 * 2 = 1116 seconds

Cutting time in 1 cycle = 5425 seconds

= 90.4 mins

TOOL 4	# Seconds on Fastest Machine	* # repetitions	* 2 pallets
PLD SUBFINISH Unit 1	76	76 * 9 = 684 seconds	684 * 2 = 1368 seconds
PLD Subfinish unit 2	28	28 * 9 = 252 seconds	252 * 2 = 504 seconds
PLD Subfinish unit 3	42	42 * 9 = 378 seconds	378* 2 = 756 seconds

Cutting time in 1 cycle = 2628 seconds

= 43.8 mins

TOOL 6	# Seconds on Fastest Machine	* # repetitions	* 2 pallets
PLD subrough Unit 3 - 4	65	65 * 3 = 195 seconds	195 * 2 = 390 seconds
PLD Subfinish unit 4	24	24 * 9 = 216 seconds	216* 2 = 432 seconds
PLD rails unit 1-2	26	26 * 3 = 78 seconds	78* 2 = 156 seconds

Cutting time in 1 cycle = 978 seconds

= 16.3 mins

TOOL 8	# Seconds on Fastest Machine	* # repetitions	* 2 pallets
PLD subpocket unit 3-4	188	188 * 9 = 1692 seconds	1692 * 2 = 3384 seconds

Cutting time in 1 cycle = 3384 seconds

= 56.4 mins

TOOL 15	# Seconds on Fastest Machine	* # repetitions	* 2 pallets
PLD subfinish Unit 7-10	163	65 * 9 = 1467 seconds	1467 * 2 = 2934 seconds

Cutting time in 1 cycle = 2934 seconds

= 48.9 mins