Process Improvements during Production Ramp-up

By

Ryan W. Chew

Bachelor of Science in Mechanical Engineering, Carnegie Mellon University, 2000

Submitted to the Department of Mechanical Engineering and the MIT Sloan School of Management in
Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
and
Master of Science in Mechanical Engineering

In Conjunction with the Leaders for Manufacturing Program at the
Massachusetts Institute of Technology
June 2007
©2007 Massachusetts Institute of Technology. All rights reserved.

The author hereby grants to MIT permission to reproduce and to distribute publicly paper and
electronic copies of this thesis document in whole or in part.

Signature of Author

MIT Sloan School of Management
Department of Mechanical Engineering
May 2007

Certified by

Donald B. Rosenfield, Thesis Supervisor
Director, Leaders For Manufacturing Fellows Program

David E. Hardt, Thesis Supervisor
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering,
Department of Mechanical Engineering

Debbie Berechman
Executive Director of Masters Program

Professor Laxit Anand
Chairman, Committee on Graduate Students
Department of Mechanical Engineering
Process Improvements during Production Ramp-up

By

Ryan W. Chew

Submitted to MIT Sloan School of Management and the
Department of Mechanical Engineering on
May 6, 2007 in partial fulfillment of the requirement for the Degrees of
Master of Business Administration and
Master of Science in Mechanical Engineering

Abstract

Raytheon Company is currently ramping up production radars for a fighter aircraft. This
product is doubling production in the next year to meet customer demand; however, the
program has not been able to meet the current demand schedule for the radar. In
addition, the cost of producing this radar is over the budgeted amount. Management is
pushing cost and cycle time reductions on every piece of the radar, a task the team is
diligently working to accomplish.

The main focus of this project is one sub-assembly of the AESA radar system, the
“coldwall”, a heat sink that also provides the base structure by which all of the radar
sensing equipment is connect to. The coldwall also acts as a heat sink, reducing the
internal temperature of the radar assembly, thereby improving the fidelity of the radio
frequency signal and longevity of the system itself. Currently, the cycle time to
manufacture the coldwall is on average twice the planned cycle time and the cost is three
times the budgeted amount.

This thesis provides a case in which a process improvement investigation takes place
under tight budgetary and time constraints in ramp-up mode. The goal of this thesis is to
develop a case for accurate and complete data collection to help future process
improvement decisions. The act of focusing this investigation was cumbersome due to
the lack of data available on the process. In addition, the case study shows a situation
where proactive issue resolution and active waste elimination could alleviate the stress
incurred by cost over runs and delayed product shipments.

Thesis Supervisor: Donald Rosenfield
Title: Senior Lecturer / Director LFM Fellows Program

Thesis Supervisor: David Hardt
Title: Ralph E. and Eloise F. Cross Professor of Mechanical Engineering, Department of
Mechanical Engineering
ACKNOWLEDGEMENTS

I would like to thank the Leaders for Manufacturing program for giving me the opportunity to broaden my knowledge and giving me the tools to become a better problem solver in the future. In particular, I would like to thank my advisors Professor Donald Rosenfield and Professor David Hardt for providing their support throughout my internship.

Next, I want to thank the Raytheon Company for providing me an excellent opportunity to put all the business and operations theory I have learned into practice. In particular, I want to acknowledge Dhiren Mehta, Jeff Bayorgeon, David Shih and Dennis Coyner for providing me with the guidance and support I needed to complete this project. I would like to give a special thanks to George Kulakowski and Joel Munoz for going out of their way to offer me their wisdom and help me navigate through this problem.

Lastly, I would like to thank my family for the love and support I have received throughout my life. Without the sacrifices you have made to further my education and career, I could not have made it this far. I hope to continue to make you proud!
[This page is intentionally left blank.]
# Table of Contents

1.0 Introduction ................................................................................................................ 10  
   1.1 Organization of this Thesis .................................................................................... 10  
   1.2 Problem Statement and Thesis Goal ......................................................................... 11  

2.0 Background ................................................................................................................ 13  
   2.1 Raytheon Company ................................................................................................. 13  
   2.2 Space and Airborne Systems .................................................................................. 13  
   2.3 Advanced Manufacturing Engineering .................................................................... 13  
   2.4 Actively Electronically Scanned Array Radar System ............................................. 14  

3.0 The Coldwall .............................................................................................................. 15  
   3.1 The Coldwall Manufacturing Process ...................................................................... 15  
   3.2 Project Motivation ................................................................................................. 18  

4.0 Case Study .................................................................................................................. 20  
   4.1 Data Collection ........................................................................................................ 20  
      4.1.1 Survey for Ideas and Background ...................................................................... 20  
      4.1.2 Data Collection ................................................................................................ 21  
   4.2 Cycle Time Modeling ............................................................................................... 22  
   4.3 Bottom-up Unit / Process Cost Modeling ................................................................ 24  
   4.4 Targeting Areas for Improvement .......................................................................... 25  
      4.4.1 Machining .......................................................................................................... 27  
      4.4.2 Brazing ............................................................................................................... 27  
      4.4.3 Deburring ........................................................................................................... 28  

5.0 Deburring Investigation ............................................................................................. 31  
   5.1 Deburring Options ................................................................................................... 32  
      5.1.1 Dry Blasting ....................................................................................................... 32  
      5.1.2 Wet Blasting ...................................................................................................... 32  
      5.1.3 CNC Machine .................................................................................................... 32  
      5.1.4 Chemical ........................................................................................................... 33  
      5.1.5 Thermal ............................................................................................................. 33  
      5.1.6 Electrochemical ................................................................................................. 33  
      5.1.7 Ultrasonic Vibration .......................................................................................... 34  
   5.2 CNC Deburring ....................................................................................................... 35  
   5.3 Acceptance Criteria ............................................................................................... 36  
   5.4 Medium .................................................................................................................. 37  
   5.5 CNC Settings ......................................................................................................... 38  
   5.6 Feasibility Testing and Results ............................................................................... 40  
   5.7 Results .................................................................................................................... 43  
   5.8 Next Steps .............................................................................................................. 47  

6.0 Organization and Change ............................................................................................ 50  
   6.1 Strategic Design Lens ............................................................................................. 50  
   6.2 Political Lens .......................................................................................................... 52  
   6.3 Cultural Lens .......................................................................................................... 54  

7.0 Recommendations ..................................................................................................... 55  
   7.1 Firefighting versus Proactive Issue Resolution ....................................................... 55  
   7.2 Data-driven Decision Making .................................................................................. 55  
   7.3 Waste Elimination ................................................................................................... 57
# Table of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coldwall manufacturing process</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Metal burr formation</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>Planned versus Actual Cycle Time</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>Unit cost breakdown including rework and external support</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>Unit cost breakdown by process step not including rework and external support.</td>
<td>26</td>
</tr>
<tr>
<td>6</td>
<td>Initial targeted processes highlighted</td>
<td>29</td>
</tr>
<tr>
<td>7</td>
<td>Hole Burr Formation</td>
<td>29</td>
</tr>
<tr>
<td>8</td>
<td>Deburring options with relative cost, effectiveness and potential plant disruptions compared.</td>
<td>35</td>
</tr>
<tr>
<td>9</td>
<td>Burr removal</td>
<td>39</td>
</tr>
<tr>
<td>10</td>
<td>Brush path overlap</td>
<td>40</td>
</tr>
<tr>
<td>11</td>
<td>Critical deburr locations</td>
<td>42</td>
</tr>
<tr>
<td>12</td>
<td>Nylon Abrasive Filament brushes: Disc and End brushes</td>
<td>42</td>
</tr>
<tr>
<td>13</td>
<td>Edge rounding differences between manual and automatic deburring methods.</td>
<td>44</td>
</tr>
<tr>
<td>14</td>
<td>Impressions taken of hole edges</td>
<td>44</td>
</tr>
<tr>
<td>15</td>
<td>Surface finish comparison between automatic (left) and manual (right) deburring methods.</td>
<td>45</td>
</tr>
<tr>
<td>16</td>
<td>Unit cost breakdown by process step after automatic deburr is fully implemented</td>
<td>46</td>
</tr>
<tr>
<td>17</td>
<td>DOE Settings for Surface Deburring</td>
<td>47</td>
</tr>
<tr>
<td>18</td>
<td>DOE Settings for Pocket Deburring</td>
<td>48</td>
</tr>
</tbody>
</table>
1.0 Introduction

This thesis represents the results of a 6 month project completed at Raytheon Company’s Space and Airborne Systems (SAS) division in El Segundo, California between June and December of 2006. This project was sponsored by Raytheon’s Space and Airborne System’s Advanced Manufacturing Engineering (AME) and Array Manufacturing and Development (AM&D) organizations. The focus of this project was to understand the production issues involved in manufacturing a sub-assembly of a current production radar system ramping up to full production while simultaneously working to improve the throughput, quality and cost of producing this sub-assembly. This project is one of many Leaders for Manufacturing (LFM) projects undertaken as a part of the Raytheon and LFM partnership.

1.1 Organization of this Thesis

This thesis attempts to summarize the methods, thoughts, learnings and findings associated with an effort to improve productivity on a specific radar subassembly in production ramp-up mode.

Chapter 1 discusses the problem statement and thesis goal.

Chapter 2 discusses the background and environment by which this project is undertaken. This context helps to better understand the challenges that were faced in completing this project.

Chapter 3 describes the product and manufacturing process that this study will use as a springboard into a process improvement investigation.
Chapter 4 dives into the case study by looking into at how data was collected and analyzed to better understand the issues surrounding the coldwall production process. Then, based on the analysis, the three potential improvement areas are discussed.

Chapter 5 discusses a specific process improvement investigation by better understanding the challenges faced in improving this process and the implementation steps taken to realize improvements in throughput, cost and quality.

Chapter 6 looks at the organization to understand the underlying reasons why the process improvement has been slow in the past and offers some recommendations that may help the organization tackle process improvement in the future.

Chapter 7 discusses some recommendations to the coldwall team to help aide in the continuous improvement process, such as move into a proactive problem resolution mode, use data to make decisions and eliminate waste in the production process.

Chapter 8 concludes the thesis by wrapping up the issues discussed in the previous 7 chapters.

1.2 Problem Statement and Thesis Goal

During a production ramp-up, this production team is under pressure to improve yields, while lowering the cost of production. To get up to full production, the team has improved cycle time by improving process techniques and working with design to re-engineer the part for producibility. However, continuous improvement in this particular situation is hindered by three issues: data collection methods, deficiencies in lean thinking, and organizational inefficiencies. In the past, the production improvement process was not driven by data, but more by guesses and complaints. A more data-driven approach is necessary to characterize the entire production process and better focus improvement projects. In addition, some basic lean principles will help the shop run
more efficiently by focusing personnel on finding simple solutions to waste elimination. Lastly, the organization is bogged down by constant firefighting and lack of design for manufacturing. The team needs to be more focused on continuous improvement and work with design to create products that can be easier to manufacture\(^1\). Solving these issues will help the shop increase throughput and deliver higher quality parts at a lower cost\(^2\).

The goal of this thesis is to use some basic frameworks and techniques to characterize a specific situation to find a tangible solution to a pressing need. This case will be used to depict the situation and ways these simple techniques were used to solve an issue on the shop floor. The author hopes that this paper can help those in similar situation better understand the issues they are plagued with and find simpler solutions to their production problems.
2.0 Background

2.1 Raytheon Company

Raytheon Company (NYSE: RTN), with $21.9 billion in sales in 2005, is an industry leader in defense and government electronics, space, information technology, technical services, and business aviation and special mission aircraft. Its headquarters is in Waltham, Massachusetts, has seven core businesses, and employs 80,000 people worldwide. Raytheon strives to be the most admired defense and aerospace systems supplier through world-class people and technology.

2.2 Space and Airborne Systems

The Space and Airborne Systems (SAS) segment, headquartered in El Segundo, California, provides electro-optic/infrared sensors, airborne radars, solid state high energy lasers, precision guidance systems, electronic warfare systems, and space-qualified systems for civil and military applications. This segment earned $4.3 billion in revenues in 2005 and employs 12,000 people in 3 states. SAS has key capabilities in airborne radars and processors, electro-optic/infrared sensors, electronic warfare and precision guidance systems, active electronically scanned (AESA) radars, space and missile defense technology and intelligence, surveillance and reconnaissance (ISR) systems.

2.3 Advanced Manufacturing Engineering

The Advanced Manufacturing Engineering (AME) organization was recently established to fill in a gap between the design, supply chain and production groups at SAS. It is AME’s goal to improve the following issues that have caused problems at SAS: best
practice sharing between organizations and programs, proactive problem solving, and standardization of practices and processes. AME is comprised of 4 groups: Advanced Manufacturing Technologies, Manufacturing Engineering, Industrial Engineering and Planning and Technical Staff. AME was the main sponsor of this project and provided the technical experts, resources and data needed to complete this project.

### 2.4 Actively Electronically Scanned Array Radar System

This project focuses on one of Raytheon’s Actively Electronically Scanned Array (AESA) Radar systems, which “represents a significant advance in radar technology.” Entirely new from front-end array to back-end processor and operational software, the system substantially increases the power of an aircraft, making it more lethal and less vulnerable than ever before.

With its active electronic beam scanning — which allows the radar beam to be steered at nearly the speed of light — these radar systems optimize situational awareness and provides superior air-to-air and air-to-ground capability. The agile beam enables the radar’s air-to-air and air-to-ground modes to interleave in near-real time, so that pilot and crew can use both modes simultaneously, an unprecedented technological leap.
3.0 The Coldwall

The main focus of this project is on the "coldwall", one of the main sub-assemblies on the AESA. The coldwall provides the base structure by which all of the radar sensing modules are connect to. In addition, the coldwall also acts as a heat sink, reducing the internal temperature of the radar assembly, thereby improving the fidelity of the radio frequency signal and longevity of the system itself. While many coldwalls exist in the field, each coldwall is unique to the application of the radar system. In addition, coinciding with each radar system becoming more and more technologically advanced, the coldwall is becoming more complex, pushing the limits of design and manufacturing in this specific application.

3.1 The Coldwall Manufacturing Process

The manufacture of the coldwall goes through the following steps:

1. Detail Manufacture
2. Brazing
3. Inspection and Cleaning
4. CNC Machining
5. Deburr
6. Chromate
7. Inspection and Repair

![Figure 1: Coldwall manufacturing process.](image)
The coldwall is a complex machined aluminum block with channels used to house cooling liquid. The coldwall starts out as four square sheets of aluminum alloy of various thicknesses. Each of the 4 sheets of aluminum has different material properties, such as hardness, thickness and the type of clad material. The 4 layers are machined separately to provide the inner and outer structure of the coldwall assembly. Each layer is then manually deburred, degreased and deoxidized. If the parts are not deburred and cleaned thoroughly, the presence of any foreign material or burrs may get affect how the layers braze together, either by causing the layers to not braze properly or by blocking coolant flow through the coolant channels.

Brazing is a joining process by which a soft alloy is heated to a melting temperature and distributed between two close-filling parts by capillary action. Capillary action is the ability of a substance to draw up into a porous cavity against gravity. At its liquid temperature, the molten filler metal interacts with a thin layer of base metal, cooling to form a strong, sealed joint. The brazement is annealed, or cooled at a controlled rate, to create a high-strength braze joint. The brazed joint becomes a sandwich of different layers, each linked to the adjacent layers.

Once the 4 layers are brazed, the coldwall is inspected to ensure that the layers were brazed properly. After the coldwall is checked, it is sent to a chemical cleaning line where it is dipped into a series of chemical baths to cleaned, degreased and deoxidized. A clean interface between layers allows for more consistent brazing. Once this is completed, the part air dries and held until a CNC machine is ready for final machining.

This last machining step is used to create the features used to hold the radar sensing modules. In this step, approximately three quarters of the aluminum is machined away to fabricate the pockets that hold the radar sensing equipment onto the part. The machining paths are planned carefully since very tight tolerances are required for the wall thicknesses, hole diameters and edge radii. These tight tolerances are to ensure the structure does not affect the fidelity of the radar signal. If the cutter missteps and either
violates the tight tolerances or damages the part, the part would have to be scrapped since it’s very difficult to add metal back onto the coldwall. Once the coldwall is machined, it is manually deburred once again.

This manual deburring step is very manually intensive and time consuming. A shop worker uses brushes and knives to scrape off all the excess burrs on the part, which at times are difficult to see due to the depths of some of the pockets and small size of the burrs. Similar to the deburring process for the individual layers, deburring for the post brazed machined coldwall needs to be very accurate and thorough since any piece of metal left behind could get into the coolant channels and could disrupt the coolant flow, therefore not cooling the radar sensing modules effectively. This could affect the radar fidelity or cause a blind spot in the radar spectrum. In addition, leaving burrs on the part is a safety concern as it can injure someone that does not know it is there. Manual deburring will be revisited throughout this paper, as it becomes the main focus of this process improvement effort.

Once the coldwall is thoroughly deburred, the part goes through a series of steps to prepare the part for delivery to the downstream assembly areas. First, part goes through a chromate process. Chromate is a process by which a coating is applied to metals to protect the metal from corrosion. Next the part has hardware assembled to it. And finally, the part goes through paint process by which all the necessary markings and verbiage are stenciled onto the coldwall.
Throughout the process, the coldwall is constantly inspected to ensure that all the critical features are within tolerance and no damage has occurred on the part itself. In addition, after each major step, the coldwall goes through a series of pressure drop tests to ensure consistent and accurate fluid flow through the coolant channels. Since the fluid is flowing through closed loop system, the pressure within the channels must stay within a specific pressure drop level. If the pressure drop extends past a certain level, this means that either the coolant through the system is not flowing properly or there is a leak in the system. To test for a leak in the system, inspectors use helium to detect leaks. Once these leaks are found, the metal is repaired and tested again to make sure the leak was fixed. If the leaks cannot be fixed, the coldwall is unfortunately scrapped.

**3.2 Project Motivation**

This radar system has been designed to be state of the art, pushing out the boundaries of radar technology. Raytheon has produced less complex radars using these same production methods for years. However, this new radar system is pushing the limits of the antiquated (some more than 20 years old) machinery on the shop floor. The coldwall’s tolerances are very close to the designed tolerances of the vintage CNC machinery.

In ramp-up mode, the coldwall is pacing the production of this radar system. Since this coldwall has launched a year ago, due to an increasing demand schedule and constant firefighting, the team has struggled to produce coldwalls under its planned cost budget and cycle time. This is typical in the aerospace industry as the low volume high mix nature magnifies and expands the number of natural pitfalls early in the production cycle\(^4\). Before this project started, the average cost of producing the coldwall was twice the planned cost budget. In addition, the time to produce one coldwall was on average twice the planned cycle time.
In the next few years, the demand for these coldwalls will increase to double the current yearly demand for the next few years and will double again a few years later. If the team continues to produce coldwalls without improving the production methods, the team will not be able to meet demand. In addition, the cost of producing the coldwall is continuing to spiral out of control. Costs need to be controlled to improve the viability of producing these coldwalls.
4.0 Case Study

The coldwall was used as a case study to investigate process improvement on a low volume production product. First, qualitative and quantitative data was collected and analyzed using cycle time and process cost analysis to gain a better picture of the current production problems and better focus areas for improvement. Next, once target areas were identified, one specific process was picked to provide the basis for this case study. Then, potential process improvement methods were researched and tested for effectiveness. Once the method proved to be a viable option, the method was implemented on the shop floor.

4.1 Data Collection

To start the investigation, both qualitative and quantitative data needed to be collected to better understanding of the difference between the planned and actual production performance on the shop floor. In the past, the process improvement decisions were made based on complaints and hunches by shop personnel. Collecting more accurate cycle time and cost data on the process will not only focus the process improvement task by targeting specific problem areas, but will gain a better understanding of the effects of such improvements. Without the data to drive these decisions, the outcome of process improvement is difficult to predict.

4.1.1 Survey for Ideas and Background

To better understand the processes and issues on the shop floor, all of the shop floor and manufacturing engineering personnel were interviewed. It is important to understand the all of the current issues before a more focused plan could be formulated. In addition, background information on the past and current process improvement activities needed to be known so duplication of effort did not occur.
The area the team wanted to focus process improvement efforts on was brazing process, which melds the 4 layers into one. To the team, this seemed to be the most problematic process since they were having trouble with the braze oven and the process took the help of at least 3 people at a time. However, after creating the bottom up cycle time and cost models, the braze process seems to be a minor portion of the total cost and cycle time. In addition, the solution seems to be an age of equipment issue. The braze oven is decades old and needs to be refurbished.

Therefore, the braze process did not become a focus of this project since the solution seems to be more straightforward. The only issue is funding and the team did not have the funds for a capital investment. Instead, focusing on the processes with high direct labor costs and longer than budgeted cycle time could get more tangible results with lower capital investment.

4.1.2 Data Collection

The manufacturing team has been tasked to produce a process improvement roadmap that management could use to track the cost and cycle time reduction effort. In the past, the means of deciding which process improvement projects to undertake was not data-driven, but instead by gut feeling and consulting the people on the floor. However, the issues that people targeted in the past were mostly by complaints, meaning the processes that gave the shop floor workers the most trouble. However, since this was not a data driven decision, the cost, throughput and quality impacts of these decisions were not immediately known. In addition, issues with individual process steps were hidden since data on cycle time and cost were collected in aggregate. Detailed cost information about the individual process steps will aide better decisions about how to control costs by understanding variances (cost and throughput) and can aide in future pricing determination.
To better understand how to improve the production of the coldwall, the team needed to breakdown the production process, understand the actual cost of producing each coldwall, and the average cycle time of producing the coldwall from sheet metal to delivery. However, this proved to be a difficult task since the only data tracked on the cost of producing the coldwall is in aggregate form, meaning, the finance team tracks how much the overall program costs, but the ability to breakdown the data into either a per unit or per process step cost did not exist. In addition, the shop floor collects data in paper form using a tracking sheet, which was not very accurate.

A paper packet follows the coldwall through production, which includes the specific production guidelines and instructions, testing and inspection documentation, sign-off sheets. The sign-off sheets track what day the coldwall competes a specific process step and the signature or stamp of the shop floor worker that completed that step. This method of tracking has caused the team problems because this method does not allow for accurate investigation into the actual time it took to complete a step. Since the date stamp is only tracked at the end of the process, queue time is imbedded in the process time. In addition, this date stamp causes problems when trying to understand the labor used in producing the coldwall. Since actual touch time is used in calculating the cost of producing the coldwall, process time with queue time imbedded in it is cannot accurately display the actual touch labor required in each process step.

4.2 Cycle Time Modeling

In addition to understanding which process steps were the main cost drivers, a study to find the average cycle time of producing the coldwall was necessary. Reducing cycle time will not only delivery time, but will also reduce the cost to produce as manpower required to track and process parts through the system will decrease. Since the cycle times for the parts process through the system was not readily available, the paper tracking packets had to be collected to collect data on the start ands top times for each process step for each of the units produced this past year. The past year’s units were used
because the cycle times were highly variable before 2006. In addition, there have been some engineering changes prior to 2006 that have improved the production time. The coldwall in a steady state wanted to be studied so that all recent process and product changes and special cause variations could be accounted for.

Once the average processing time for each step is known, the overall cycle time for the coldwall could be calculated. Then, the actual cycle time is compared to the initial estimations for the cycle time required to produce the coldwall. This helps focus the process improvement effort on the processes that are taking more than the initial cycle time estimations.

Due to the paper system, an issue that arose in that it is difficult to split the queuing time and the actual touch labor time. Having queuing imbedded in the process time does not accurately show how much time a process truly takes. The team noted that a queue buildup could be due to various reasons, such as machine uptime, a queue of parts waiting for the process or availability of manpower to process parts. Therefore, in these calculations, it is difficult to tell if cycle times improved due to reduced demand on the shop floor or due to actual improvements in cycle time. This is another reason why only 2006 data was used. Demand for the other products using the same assets during 2006 was fairly steady.
4.3 Bottom-up Unit / Process Cost Modeling

To better understand how much each process step contributes to the overall cost of producing the coldwall, we had to find other means of estimating the actual cost. To estimate the cost, a bottom up activity-based cost model had to be developed. This should create a more complete picture of the main cost drivers and better target future improvement actions. This task was difficult as the costs were not broken down to allow for easy comparisons between the actual and budgeted costs for the individual process steps.

The first step was to find the labor hour’s breakdown for this program. Data was collected for the last two years since the process and demand has been relatively stable since January 2005. The finance team tracked weekly who and how much each of the laborers worked on the specific program. After this data was collected for the entire year, the list of laborers was divided into groups by the process step they typically worked on. Then after totaling the labor hours for each process step, an estimate of how much that
process step cost was known for the year. In addition, the labor hours were broken up into weekly hours worked.

Once an approximation of the cost of each process step since the beginning of the year is known, an estimate of the year’s production had to be calculated. Since this data is not collected digitally, a dive into the paper tracking packets helped total how many times and approximately how long it took for the year’s units to go through a specific process step. Since production fluctuated and was not steady over the past two years, a monthly breakdown was necessary to match the units produced in that month to the hours worked that month. Then after having the total labor hours spent on a specific process and the number of units that have gone through that process step, an estimated the cost of each process is calculated by month in the last two years by the burden rate for each of those years. Once the purchased cost for material and third party services were added, an estimate for the unit cost is known.

![Percentage of Total Cost](image)

Figure 4: Unit cost breakdown including rework and external support.

### 4.4 Targeting Areas for Improvement
Certain cost elements needed to be extracted from documented aggregated overall costs to understand how the direct costs of producing the coldwall, and looking forward, how much the coldwall should cost assuming the team improves yield and eliminates rework and its associated staffing and material costs. To do this, the labor costs were broken down into engineering support, production support, scrap and rework costs in addition to the various process steps. After collecting all the relevant data and comparing it to the initial budgeted costs and cycle time, three process steps stand out as areas to focus process improvements:

- Machining
- Brazing
- Deburring.

However, to focus this effort further into a project that could be completed in the project timeframe, issues such as level of organizational change, possible infrastructure changes and engineering/design complexity need to be weighed.

Figure 5: Unit cost breakdown by process step not including rework and external support. Initial targeted processes highlighted.
4.4.1 Machining

The coldwall is a heavily machined part that is 10% of the overall cycle time. Once the coldwall is completely machined, 75% of the original mass of the part is removed. Due to the complexity and tight specifications of the coldwall features, the CNC machine cutter paths are engineered with reliability and speed in mind. The team has spent the last year optimizing the cutter paths to improve the cycle time and further optimization would require either design changes or new machinery. In addition, added cutter paths were added to aide in removing burrs from the various features in the coldwall.

Machining is the largest cost driver, as machining the individual details and the brazed assembly comprises 38% of the total cost of producing the coldwall. However, further optimizing the machine paths will not be a focus of this project as the team has reduced the machining cycle time significantly in the past and has achieved a great balance between reliability and speed. In addition, an attempt to further improve machining will require redesigns to the coldwall that may affect the functionality of the coldwall, such as either removal or changing the dimensions of certain part features.

4.4.2 Brazing

The braze process is the second largest cost driver on the coldwall. The reason for this is the braze process requires the work of multiple people to complete a series of assembly and preparation steps before the layers are welded together.

In addition to the 4 machined layers that are assembled to form the coldwall, hundreds of small parts are placed in between two middle layers of the coldwall to improve the functionality of the coldwall. This process is challenging since if the parts are not properly aligned, the part would be scrapped since it cannot be fixed once the layers are brazed together. In addition, the layers are cleaned several times to ensure all of the dirt,
grease and oxidization is removed from the surface of the layers to ensure proper brazing in the oven. Lastly, due to the size of the coldwall, the preparation and operation the braze oven requires a few people to assemble the periphery parts to hold the coldwall in place, attach the thermocouples to monitor the internal temperature, and insert the braze envelope into the oven. Lastly, once brazing is completed, a couple of people are required to remove and inspect the brazed sub-assembly.

After some investigation, other than cost, the main issues regarding brazing is the reliability of the braze oven and the assembly of the small parts sandwiched in between the layers. Although the braze oven temperature is constantly monitored, due to the age of the oven, at times, the temperature goes above the acceptable limit, causing excessive flow of the molten metal between the layers, blocking the coolant flow cavities between the layers of the coldwall. Once this happens, the coldwall is scrapped. To fix this would require large capital expenditures, funds that this group does not have access to at the time of this project. A proposal for a new braze oven is in progress, and if approved, should improve the reliability and therefore improve yield of the coldwall. Therefore, although the braze process is a large cost driver, it will not be a focus of this project.

The second issue regarding the coldwall is the small parts stacked in between the layers of the coldwall that improve the heat transfer of the coolant flowing through the coldwall. This is an ease of assembly issue since the current design allows for the parts to shift and get misaligned when the layers are brazed. This redesign is in process and should be completed soon.

### 4.4.3 Deburring

The deburring process is the third highest cost driver. Burr formation is an unavoidable result of metal cutting\(^6\). For metal milling, burrs form due to plastic deformation incurred by the cutting process\(^7\). Instead of the metal chipping away, the metal can either tear or rollover, leaving a burr on the edge\(^8\) (Figure 6). In the case of drilling holes through
metal, a burr forms on the corners of metal because when a chisel edge reaches its maximum elongation, it starts to tear and finally the drill breaks through and the remaining metal is bent out and becomes a burr (Figure 7).

Figure 6: Tear and Rollover Burr Formation.

Figure 7: Hole Burr Formation.

Manual deburring consists of the operator visually finding burrs on surface, hole and wall edges and manually removing these burrs by using scouring pads, knives and tweezers. The process is highly manually intensive, is a current ergonomic concern and is highly unreliable. Since the operators are trying to visually find and remove these microscopic burrs, burrs are easily missed and poses problems downstream if not completed properly. In addition, the task requires certain competencies for the operator to be effective and reliable.

If these burrs come off and get caught in the cooling channels, it may block a channel and affect the functionality of the coldwall. In addition, burrs may affect brazing as burrs can get between the braze joints, affecting how well the brazed joint holds welds together. This could cause leaks in the future. Lastly, burrs may affect the parts assembled to the coldwall, such as RF modules, screws and periphery parts.
Deburring will be the main focus of this project. Manual deburring is a non-value added activity that could be done faster, cheaper and more reliably by using a more technologically advanced solution. If this automated method is successful, the cost of deburring will be reduced significantly, the queue buildups in front of the manual deburring station will be eliminated and more consistent and reliable burr removal will occur, potentially resulting in less rework. The next chapter will discuss alternative deburring methods, selection criteria, and some test data.
5.0 Deburring Investigation

Before investigating deburring methods, appropriate selection criteria needed to be developed. For the coldwall, there were three important factors that needed to be weighed when choosing a new deburring method:

- Cost
- Effectiveness
- Effect on current shop operations

Due to the cost constraints on the program, an inexpensive solution needed to be developed. The cost of the various solutions ranges from a few dollars to hundreds of thousands of dollars. In addition, some methods require the additional purchase of infrastructure, such as piping and ventilation, and variable costs, such as projectile media and chemicals. Therefore the cost of a solution needs to be balanced by its effectiveness.

Another important factor is the effectiveness of the deburring method. The coldwall has many edges (e.g. holes and walls) that must keep a sharp edge (i.e. tight tolerance). Rounding of edges will degrade the RF signal and affect part assembly. In addition, the deburring method must have a uniform removal of burrs, meaning, deburring must be consistent on the surface edges and deep inside the pockets. Lastly, the method must not have the potential of damaging the part in any way.

The last determining factor to consider is how the new method effects daily operations on the shop floor. The shop has limited floor space. Therefore, the machine purchased must be small enough to fit in the tight spaces available in the shop. In addition, the method must be easy to use and require little training. The plant is pretty lean currently and therefore, the new method must not take people away from their daily tasks. Lastly, and the new method should have broad applicability. The method must be able to be effective for products with a variety of sizes, features and metals.
5.1 Deburring Options

There are many automatic deburring methods that are used in the industry. The following is a list of methods that were researched for its potential use for this particular application.

5.1.1 Dry Blasting

Abrasive blasting can be done either wet or dry. The stream of abrasive material, propelled by air pressure, can be focused on a specific area or applied fan-like to an entire part or part surface. Both metallic and nonmetallic abrasives are used.

5.1.2 Wet Blasting

In wet applications the abrasive is applied as a slurry usually with water as the liquid, along with rust inhibitors if required. The process is considered a precision method in that part tolerance can be maintained.

5.1.3 CNC Machine

Power brushing is both a fast and relatively low cost deburring method. Brushes are made of metal filaments or wire and may also be of non-metallic or synthetic materials. Common metal filament brushes can be of hi-strength and stainless steel as well as brass, copper, nickel, and other alloys. A common synthetic brush material is nylon. Brushes come in a variety of shapes and sizes for numerous applications. Power brush
aggressiveness depends on filament diameter, free length configuration, the texture, density, and bristle material type, wheel width, brush velocity, and work piece contact.

5.1.4 Chemical

In the chemical deburring process the work pieces are fully automatically dipped into subsequent baths. By means of this simple dipping treatment all burrs are removed and a surface with an optimal even level as well as round edges of perfect quality is obtained.

5.1.5 Thermal

Thermal Energy Machining process uses intense heat to deburr and/or deflash work parts of all shapes and sizes. Parts to be processed are sealed in a chamber that is pressurized with a mixture of natural gas and oxygen. The mixture is ignited by a spark plug, creating an intense burst of energy, that completely burning away burrs and flashing without harming the remaining work piece.

5.1.6 Electrochemical

In the electro-chemical deburring process burrs are dissolved by the action of a neutral-salt electrolyte flowing through the gap between the tool or cathode and the work piece which is the anode. This is a very fast, precision process. The amount of material removed is proportional to the amount of time and levels of current applied. The dissolved metal, in the form of hydroxides, is carried away by the controlled flow of the electrolyte, which is then filtered for reuse. Electro-chemical electrodes are made of copper-tungsten. The work piece areas not being deburred are insulated by a non-conductive material.
5.1.7 Ultrasonic Vibration

Ultrasonic vibration propagates in the liquid medium and, as a result, a large number of bubbles are formed. These bubbles generate an extremely strong force, which removes burrs from work pieces.

Many of these deburring methods could be used if the coldwall could be redesigned to accommodate the various methods. For example, chemical deburring is a very effective method of removing burrs in industry. Chemical deburring removes burrs by dipping the part into a chemical bath, uniformly removing a thin layer from the surface. This leaves a very clean surface. However, to implement this process, the part would need to be redesigned and the machining automation program would have to be adjusted with this layer removal in mind. To do this, would require added costs, development time and a government buy-off, which is a very lengthy process for a current production part.

However, some automatic deburring methods were quickly eliminated for the following reasons:

- Ultrasonic vibration is typically used on small parts.
- Electrochemical deburring is used widely in industry, but this method is known to create large edge radius and can contaminate parts with a residue.
- Thermal deburring is typically used on parts much smaller than the coldwalls used for radars.
- Chemical deburring was eliminated because this method requires a dip into a chemical bath. If the chemical seeps into the coolant channels, then it would be very difficult to remove the chemical. The chemical used in deburring could react with the coolant used to facilitate heat transfer and could reduce its effectiveness.

The upfront capital costs and potential part and process redesign costs made all the above processes less likely to be investigated at this stage of the project.
### Hand Deburring

<table>
<thead>
<tr>
<th>Cost</th>
<th>Effectiveness</th>
<th>Plant Disruptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High labor cost</td>
<td>Highly variable. Part damage potential.</td>
<td>None. Current method used.</td>
</tr>
</tbody>
</table>

### Blasting - Dry

<table>
<thead>
<tr>
<th>Cost</th>
<th>Effectiveness</th>
<th>Plant Disruptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High capital cost, High to low variable cost</td>
<td>Large burrs only</td>
<td>Requires Floor Space, infrastructure, training. Flexible</td>
</tr>
</tbody>
</table>

### Blasting - Wet

<table>
<thead>
<tr>
<th>Cost</th>
<th>Effectiveness</th>
<th>Plant Disruptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High capital cost, High to low variable cost</td>
<td>Media affects effectiveness.</td>
<td>Requires Floor Space, infrastructure, training. Flexible</td>
</tr>
</tbody>
</table>

### CNC Machine

<table>
<thead>
<tr>
<th>Cost</th>
<th>Effectiveness</th>
<th>Plant Disruptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Does not work in narrow pockets.</td>
<td>Requires CNC programming, training</td>
</tr>
</tbody>
</table>

### Chemical

<table>
<thead>
<tr>
<th>Cost</th>
<th>Effectiveness</th>
<th>Plant Disruptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High capital cost, high variable cost</td>
<td>Cannot be used on parts with closed channels</td>
<td>Requires Floor Space, infrastructure, training. Flexible.</td>
</tr>
</tbody>
</table>

### Thermal

<table>
<thead>
<tr>
<th>Cost</th>
<th>Effectiveness</th>
<th>Plant Disruptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High capital cost, low variable cost</td>
<td>Works only for small parts</td>
<td>Requires Floor Space, infrastructure, training.</td>
</tr>
</tbody>
</table>

### Electrochemical

<table>
<thead>
<tr>
<th>Cost</th>
<th>Effectiveness</th>
<th>Plant Disruptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High capital cost, low variable cost</td>
<td>Can contaminate part with residue, creates radius.</td>
<td>Requires Floor Space, infrastructure, training.</td>
</tr>
</tbody>
</table>

### Ultrasonic Vibration

<table>
<thead>
<tr>
<th>Cost</th>
<th>Effectiveness</th>
<th>Plant Disruptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High capital cost, low variable cost</td>
<td>Can damage part with transducers, can affect finish, and is user dependent.</td>
<td>Requires Floor Space, infrastructure, training.</td>
</tr>
</tbody>
</table>

Figure 8: Deburring options with relative cost, effectiveness and potential plant disruptions compared.

### 5.2 CNC Deburring

After an investigation into various automated and manual deburring methods, the decision was to test an automatic deburring method that would not disrupt shop operations, would not require a large capital investment and could be broadly applied to multiple vintages and styles of CNC machinery for multiple product lines. Since current production was running and behind schedule, the new deburring method needed to be implemented quickly without shutting down machinery for a significant amount of time.

Therefore, the team decided to start testing a deburring method that used existing CNC machines because this could be quickly tested and implemented, was a cost effective solution and had the potential to be applied to other programs running in the shop. This
decision was not easy since there was a high level of risk involved due to the potential for
damage and time wasted if this method was not effective. However, due to the time and
cost constraints on the project, this seemed to be the best alternative.

5.3 Acceptance Criteria

Once the decision to deburr the coldwall using the CNC machine was made, the type of
deburring medium needed to be found. There are multiple options available that are used
in industry, such as clay tools and brushes, used for a variety of purposes. Similar to the
general deburring method, the specific CNC medium to use depended on three factors:

- Effectiveness
- Damage potential
- Flexibility

The most important factor is that the method is effective in removing burrs. The burr
removal method must cleanly shear off the burr formed during machining and leave
behind a sharp edge. In addition, burr removal must be consistent and reliable.
Otherwise, the benefit of reducing manual deburring is negated by the added need to
increase inspection and potential rework due to lack of burr removal.

In addition, some of these methods could damage parts, by either removing too much
metal from edges and surface areas, or imbedding the metal burrs into the part itself. The
removal process must not affect the tight tolerances of the part, such as sharp edges and
surface finish. In addition, some deburring methods may potentially imbed metal shards
into the metal surface. This must be monitored closely ensure this does not happen.

Lastly, although we are implementing this method on one product line, the goal is to
leverage this method to cut costs and more reliably deburr parts for other product lines.
Therefore, the method should be applicable to other product lines on existing CNC machinery.

### 5.4 Medium

There are many types of deburring medium used in CNC machines, where the medium used is dependent on the part composition, durability and removal effectiveness. The medium used will be brushes, since it provides the right balance of flexibility, durability and cost. In addition, this is an effective method that is widely available and used for many deburring applications in the industry.

There are many brushes available that have a wide range of applications and vary by size, material and cost\(^\text{12}\). Brushes consist of two main parts, the filament type and mounting hardware. The filament ranges from a variety of artificial to natural materials and the type of filament used depends on the application. The type of material and the grit size of the medium on the filament determine the aggressiveness of the filament\(^\text{13}\). The materials typically used for NAF is usually silicon carbide or aluminum oxide. Grit size typically ranges from 46 to 600-grit for round filaments and 80- to 320-grit for rectangular filaments, where the smaller the grit number corresponds to coarser or larger grit particles. The brush mounting typical come in the following forms: cup, end, radial and spiral. The mounting to use depends on the application and the features of the part.

The brushes that would be required for this process would have to be very specific material properties, such as a coating that would shear a burr, but soft enough to not to remove additional material from the work piece. In addition, the brushes have to be flexible enough to bend into the various crevices and holes of the coldwall, but not so strong that it damages the part by affecting the tolerances or the plating on the part itself. And lastly, the brush used must be durable for repeated usage.
5.5 CNC Settings

The last element is the settings to the CNC machine. There are a number of parameters that need to be dialed in to the programming of the brush path to optimize coverage and speed. The following are the main settings to dial in:

- Dwell time
- Rotation direction
- Depth
- Path overlap
- Coolant method

The time the brush touches the metal, or dwell time, is a function of the feed rate and angular velocity. The speed of the dwell time must be balanced by the ability for the brush to hit every surface for burr removal. If the feed rate is fast, your cycle time will be short, but the brush may not have enough time to hit every edge to remove the burrs. The brush filaments must have time to move across every edge and shear the burr off the edge. If the feed rate is too fast, the brush may pass over the burr. However, if the feed rate is too slow, the brush will be more effective in removing the burrs, but your cycle time will increase. Burr removal increases as the angular velocity increases. However, the faster the angular velocity (depending on the medium used) the more rounded the edges will become.

To remove the burr, the brush needs to rotate opposite the direction the cutter during machining. For the burr to shear, the brush needs to fold the burr over itself. Otherwise, the brush may push the burr instead of shearing off the burr. In machining, typically the cutter rotates in a clockwise manner. Therefore, ideally, the machine should rotate the brush counterclockwise to more effectively deburr the part. Since brushes are in a circular pattern, there will be points on the edge, where the brush face is moving in a counterclockwise manner, but the bristles will be moving in the same direction as the cutter. The amount of path overlap (discussed below) can help correct this.
Due to counter clockwise cutter direction, clockwise brush motion would fold burr down.

Counterclockwise brush movement will push the burr up, allowing the burr to shear off.

Figure 9: Burr removal.

Another parameter that needs to be tuned is the depth of the brush past the surface of the part. In the case of an edge, the transition of the brush filaments from a surface, over the edge and into the crevice and visa versa is how the filaments will shear off the burr. At any given time, a section of the brush filaments will either be pushed into the part and the rest of the filaments will be into the channels machined into the part. If the brush only touches the surface, the filaments will not be able to transition over the edges and shear off the burr. However, if the depth is too deep (depending on the medium used) the brush filaments will push against the edges longer, potentially rounding the edges.

The path the brush makes over the part depends on the size and shape of both the brush and the part, as the smaller the brush and the larger the part, the more switch backs the brush needs to make. Therefore, the brush path needs to be optimized for speed and uniform coverage. To do this, amount the path doubles back on itself - or overlaps a previous path - will have an effect on the dwell time and cycle time. If the path has a significant amount of overlap, the dwell time and cycle time increase. If the overlap decreases, the cycle time increases, but the dwell time may not be adequate for complete removal of the burrs. However, this can be balanced by either increasing the angular velocity or slowing down the feed rate.
Most CNC machines use either a lubricant or an air jet to cool down the cutter while it is removing material and assist in the removal of the metal shards. The decision to use the lubricant or the air jet will depend on the shape of the part. If the brush can remove and push away the burr, then a lubricant may not be necessary. However, if the shape of the part keeps the removed burr on the surface, then this could get caught between the filaments, which could scratch or damage the surface or edges of the part.

### 5.6 Feasibility Testing and Results

To test the feasibility of the new CNC brush deburring method, trials on sample products were conducted. During production ramp-up, a trade-off between experiments and production exist due to the lack of capacity and high cost of conducting such experiments\(^\text{14}\). Learning early on in the ramp-up cycle will increase the learning curve where faster ramp-up to full production with higher quality and lower costs will result. This feasibility study does use a small sample size due to lack of available parts and use of non-destructive measuring and testing. The parts currently through the system could not be used for testing and most scrapped parts were destroyed almost immediately after the defect was found. However, some scrap parts were found and a few test parts were fabricated for testing. Although the sample size is small in testing, the results were robust and consistent enough to move ahead to implementation.
To test the effectiveness (and viability) of brushes, a series of tests were performed.
First, various brushes were purchased to gain a better understanding of what the best option for this application would be. Second, the brush path and CNC machine parameters needed to be tested on sample parts to understand how effective the brush would be. Then finally, the results needed to be inspected and compared to the current manual deburring method. Note that these tests were performed during current production was running throughout the day. Small time windows were made available to fit in these tests. So in this case, many of the decisions were made based on best engineering judgment and the collective knowledge of the team assembled.

To test viable brush options, two types of brushes were purchased in various sizes: plastic and nylon abrasive filament brushes. The plastic brushes worked well for polishing the surface, but was not effective in removing the burrs. In addition, the plastic brushes were not flexible enough to conform to the surface of the part. Therefore, nylon abrasive filament brushes were tested for this specific application. Although nylon abrasive filament brushes come in a variety of grit sizes, a 180-grit (medium) was picked for initial feasibility tests.

There are three surfaces on the part that are critical areas for removing burrs: top surface edges, deep pocket surface holes and the pocket side walls. For the top surface, a large 4-inch disc brush was used to attempt to uniformly remove burrs over a variety of surface edges. The deep pockets were difficult because of the depth and location of the holes on the bottom surface. Therefore a small end brush was used that could fit into the pocket and flex enough to hit the holes in the corners of the pockets. Lastly, to save tool change over time, the end brushes were going to be tested to find out if the sides of the brush filaments could remove burrs from the side wall edges. These brushes were not designed for this application since primarily the tips of the filaments were used for deburring. To make this work, a special brush pattern would have to be developed.
Once the brush types were picked to fit this application, the CNC settings need to be developed to optimize effectiveness and speed. Two CNC brush paths were developed for the two brush types. A program using a winding zigzag motion was developed by a CNC machine programmer to cover the surface of the part. A 50% overlap was used to ensure uniform coverage and ensure that the brush will move over each edge to fold the burr over itself. If the brush only moved over an edge once, depending on where the brush hits the edge, the brush may just push the burr and not shear it over the edge. Going over the edge twice in two directions will ensure shearing occurs.

Once the basic path was completed, the feed rate, depth and rotational speed needed to be tuned in. Since the dwell time was a function of the feed rate and rotational speed, the feed rate stayed constant (30 inches/min) but we varied the rotational speed instead of varying both. After a series of rpm tests, varying from 300rpm to 1000 rpm, the edges were showing signs of rounding. To be safe, 500 rpm was used since this kept the edges
within tolerance. Lastly the depths of the brushes were tested. The depth ranged from zero to five hundredths of an inch. At 0.04 inches, all the burrs were removed, but some edge rounding occurred. However, the edge rounding was within tolerance.

For the pockets, a different path needed to be developed. The smaller end brush was used to fit inside the pockets, remove burrs on the bottom surface and at the same time clear burrs from the wall edges. Since the end brush and pocket was physically a different shape and since some of the surface holes were close to the edge, a square pattern needed to be used. Since the end brush filaments flare out a little bit, for the brush to remove burrs on the wall edges, a stepped pattern needed to be used. To compensate for a lack of variable height programming in the CNC, the pattern had to be stepped, where the brush would move along the walls along one plane, then once the brush completed its path along the edge, it would step down further into the pocket to do another pass in a lower plane. This is repeated until the brush ends hit the bottom of the pocket. Then once the brush touches the pocket, a new motion was programmed in with a set depth into the surface. Various depths at increments of 0.01 inches were tested. At depths greater than 0.03, no noticeable results occurred. Therefore, the depth was set at 0.03 inches, where burr removal was consistent and edges remained sharp. This pattern was repeated for every pocket on the part.

5.7 Results

After initial testing and inspection, the results proved that using these nylon filament brushes to automatically remove burrs was a viable method. Figure 11 shows the difference between the two methods on the hole edges. In addition, a plastic mold of an automatically deburred hole (Figure 12) was taken to measure the edge radius left by using the brush versus manual deburring. Both showed the same results: deburring using the brush left a sharp edge while the manually deburred edge was rounded. A numeric measurement for the automatic deburred edge was too small for measurement using the tools available; however, visual inspection proves to be enough to compare the
differences between the two methods. For the surface edges, some slight rounding occurred. However, the edge left behind was within tolerance and therefore should not affect part quality or effectiveness.

Figure 13: Edge rounding differences between manual and automatic deburring methods.

Figure 14: Impressions taken of hole edges.
In addition to sharp edges, a surface finish test proved to be successful. The surface finish of the pocket hole turned out to be better than the manually deburred method (Figure 11). This result makes intuitive sense, since these brushes are also used for metal polishing. Therefore, the brushes smoothed the surface lines (or machining marks) left behind by the cutter during machining.

![Surface finish comparison between automatic (left) and manual (right) deburring methods.](image)

Automatic deburring proved to remove small burrs uniformly over all of the surface, hole and wall edges. However, on some edges, large burrs were left behind due to incomplete machining, meaning the cutter did not mill completely through the thickness of the metal. Since these brushes cannot remove large burrs, the cutter paths, speeds and depths need to be tuned to aide in the removal of these burrs.

In addition, the cycle time required for deburring was reduced significantly. Using the manual deburring method, queue time and processing time for the post-brazed coldwall typically took 2 days (1 day of queue and 1 day of processing, see Figure 3). However, using automatic deburring, the entire deburring time took 1 hour including setup time, which was negligible since the change over from cutter to brush took minutes. In
addition, queue time before deburring was eliminated since deburring occurs immediately after machining. This proved to be a significant time savings.

Not only is time saved deburring the coldwall, additional savings will be realized once programs are written to deburr the four layers that comprise the coldwall. Deburring each layer should take no more than 20 minutes a piece since these layers only require surface deburring using the large disc brushes. Initial tests on 3 of these parts proved these brushes provided identical results to the coldwall. Initial estimates of these time savings should reduce deburring time by 90%, which includes queuing time and processing time. Using this logic, the total cost of deburring should also be reduced by 90%, or 15% of the total cost to produce the coldwall.

Lastly, an anticipated result from using this method is the reduction of rework due to more reliable and consistent burr removal and the elimination of human error in deburr. This should aide in more effective brazing between the aluminum layers since the burrs removed from the surface is more consistent. Therefore, leaks and foreign debris inside the channels should be reduced. However, due to time constraints on this project, these results have not been realized.
5.8 Next Steps

Due to the time constraints on this project, much more could be done to further improve the effectiveness of the nylon abrasive filament brushes used in the CNC machines. A Design of Experiments (DOE) could be completed to find the optimal combination of input parameters that would balance effectiveness, process time and brush wear for surface deburring. Varying these settings will affect the dwell time and therefore will affect the ability of the brush to shear off burrs. Our initial tests may provide the optimal settings for deburring, and therefore, more investigation needs to occur to find what settings gives us the best results.

Our initial tests show the following inputs could be varied to attempt a full factorial $2^4$ DOE for surface deburring: rotational speed, translational speed, brush depth and grit size. At this 2-level DOE, the following set of levels could be tested using center point runs set at the previously tested and accepted levels (Figure 17):

<table>
<thead>
<tr>
<th>Input</th>
<th>+ Level</th>
<th>0 Level</th>
<th>- Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational Speed</td>
<td>250 RPM</td>
<td>500 RPM</td>
<td>750 RPM</td>
</tr>
<tr>
<td>Translational Speed</td>
<td>10 inch/min</td>
<td>30 inch/min</td>
<td>50 in/min</td>
</tr>
<tr>
<td>Brush Depth</td>
<td>0.01 inches</td>
<td>0.04 inches</td>
<td>0.07 inches</td>
</tr>
<tr>
<td>Grit Size</td>
<td>120-grit (large)</td>
<td>180-grit (medium)</td>
<td>320-grit (small)</td>
</tr>
</tbody>
</table>

Figure 17: DOE Settings for Surface Deburring.

Then, there are three outputs that could be measured: brush wear (depth of filament lost), edge rounding and process time. The results of this DOE would give the team enough data to find the optimum settings for CNC machine deburring.

A similar DOE could be performed for the coldwall pockets, except it would be a full factorial $2^4$ DOE since the square deburr pattern on the pocket floor would need to be
varied to find the pattern that gives the most consistent burr removal. The translational speed at the surface would have very little effect on the quality of deburring. Instead the translational speed inside the pockets as the brush makes a square motion would have a great effect on burr removal. The outputs could be the same for surface deburring.

<table>
<thead>
<tr>
<th>Input</th>
<th>+ Level</th>
<th>0 Level</th>
<th>- Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translational Speed</td>
<td>3 inches/min</td>
<td>5 inches/min</td>
<td>7 inches/min</td>
</tr>
<tr>
<td>Square Radius</td>
<td>0.10 inches</td>
<td>0.15 inches</td>
<td>0.20 inches</td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>500 RPM</td>
<td>1000 RPM</td>
<td>1500 RPM</td>
</tr>
<tr>
<td>Brush Depth</td>
<td>0.01 inches</td>
<td>0.04 inches</td>
<td>0.07 inches</td>
</tr>
<tr>
<td>Grit Size</td>
<td>120-grit (large)</td>
<td>180-grit (medium)</td>
<td>320-grit (small)</td>
</tr>
</tbody>
</table>

**Figure 18: DOE Settings for Pocket Deburring.**

Completing these DOEs will be very cumbersome as a $2^4$ and $2^5$ full-factorial DOEs requires 16 and 32 tests, respectively. It is possible that either a reduction in effective factors or using a fractional-factorial DOE model could be used to reduce the number of tests. However, these decisions would need to be a part of the DOE analysis.

In addition to completing a DOE on the settings mentioned above, there are many other parameters that could be tested. For example, there are different types of grit material on the market that may be more effective than silicon carbide. In addition, there are different sizes of brushes that could be used that may be more effective than the 4-inch and 1-inch brushes used in this study.

Lastly, in the short term, this method should be rolled out to other products produced in this shop (and throughout Raytheon) to help other programs eliminate wasted effort, reduce cost and improve quality. Time, resources and funds need to be spent to fully investigate the applicability of this method to current programs requiring metal deburring. In the long term, further investigation into the other automatic deburring methods should be investigated for future programs. Although the capital costs may be high for the other
alternatives, as these coldwalls become increasingly complicated, a more technically advanced solution may be the only way to properly deburr these parts in the future.
6.0 Organization and Change

During the 6 month project, many organizational changes were rapidly occurring at Raytheon’s Space and Airborne Systems division. This section will use a Three Lens analysis to better understand the issues the design and manufacturing teams were facing in the past and how a recent organizational structural change has created a new atmosphere that is more conducive to continuous process improvement and rethinking the way Raytheon develops products. However, there are many more hurdles the organization needs to overcome before this organization creates true change within the organization that could be translated to other divisions at Raytheon.

6.1 Strategic Design Lens

The strategic lens views the organization as a machine designed to achieve goals and carry out tasks. Designers of the organization set strategy for the firm based on rational analysis of opportunities of capabilities. Sub-sets within the organization are grouped in clusters by task or activities and are linked (formally and informally) to other clusters depending on cross unit activities. Lastly, the means by which the groups are aligned by either incentives or metrics will help dictate future performance.

In the past, design and manufacturing were the classic siloed organizations, where design did the up front work on the product and then it was “tossed” it over the wall to manufacturing to produce. This situation proved to be a very difficult situation to work in as many issues arose due to the lack of communication between the two groups. Products were consistently late, had many quality issues and the programs were over budget on many programs. In addition, each silo has individual goals to accomplish, which did not necessarily align with the common goals of the organization.
Many people in the manufacturing organization expressed their displeasure in how recent products were developed without the proper communication and understanding of anticipated issues downstream. These groups were not properly aligned across common metrics where joint communication was valued. The coldwall is a great example of this. There are many coldwalls currently in production. However, all of them are facing the same issues: delayed deliveries, cost over runs and constant quality issues. The problems faced could have been mitigated with the proper alignment of incentives across both parties. Now, the team is constantly firefighting and not able to spend the necessary time to complete process and product improvement projects.

A year ago, the Advanced Manufacturing team was created to bridge the gap between the design and manufacturing communities. The goal was to gain knowledge about best practices in manufacturing and disseminate these ideas throughout SAS. In addition, they want to aide in the transition from design to production by better providing some leverage and pushing Design for Manufacturing and Lean Manufacturing throughout the division by making products easier to manufacture, while standardizing production methods and streamlining the supply chain. Lastly, the team is responsible for acting proactively (but usually reactively) to improve productivity and cost before either cost over runs or a delayed delivery schedule occurs.

The group has program leads that are co-located with the Production team, usually next to the Production area. This helps improve communication between the Production and Advanced Manufacturing team to quickly understand the issues and act quickly. This helps the Production team because they can work to put out fires on the floor and the Advanced Manufacturing liaison can work on the development work to improve productivity.

This transition has been difficult as this has been a paradigm shift within SAS. Adding an intermediary between design and manufacturing has not been easy for either side to get used to. There were many products in the pipeline and it will take this group some time to grow, become more established and properly align such that all three
organizations will collectively work to drive improvements throughout the organization. Because of this, the team has not been used as effectively as possible, as at times they are used as firefighters working on sustaining the status quo instead of project managers improving processes and looking proactively towards future production.

6.2 Political Lens

The political lens gives insights about an organization, where stakeholders have different goals and contradictory interests struggle for power with one another. People get things done through formations of coalitions across groups based on similar interests and goals. In addition, power shifts within an organization as the competition resources and goals and tasks are negotiation by the various parties involved.

Since the organization acts as a middle step between Engineering and Production, the Advanced Manufacturing team bounces back and forth between Engineering and Production to facilitate discussions and drive changes. This causes alignment issues as the Production and Engineering team has different goals and incentives. Engineering, historically the main driver within the company, pushes designs that cannot necessarily be built within consistently and within budget. Then the Production team is forced to deal with this and is constantly pushed to improve productivity, a task that is not necessarily easy to do, especially when the design of the product does not have manufacturability in mind. This causes great tension. Advanced Manufacturing, as the middle men, try to alleviate these issues by understanding both sides and trying to develop solutions that helps everyone. This causes a delay in any decision as both sides need to agree, which is easier said than done. The insertion of the middle man sometimes causes a slow down in the process. However, one good note is that at least the process is moving and not stagnant, as it was in the past.

Power seems to still lies in Engineering as Raytheon is a technology company where the company is in a rush to pump out the latest and greatest products. Most of the issues on
this product results from a design that is technologically sound, but not necessarily easy
to manufacture. According to the production team, they try to state their concerns up
front, but it usually falls on deaf ears. The creation of the Advanced Manufacturing team
should shift power away from the Engineering side to the Manufacturing side, as
producibility is becoming more important. There is some evidence of this as the
Advanced Manufacturing team has been able to get changes pushed through engineering
faster recently. This has been due to the proper upper management support and the
current pressures to reduce cost and throughput levied on both parties.

The power struggle is further complicated by Finance and Program Management, as they
work as the guardsmen under which all Engineering and Production must follow. They
develop the contracts and budgets and push change via cost and throughput. This causes
great pain for the Production and Advanced Manufacturing teams because both sides are
being squeezed to improve costs. This causes another alignment issue as Production and
Advanced Manufacturing are being driven by cost and throughput. Engineering, at the
moment, does not look at cost and throughput as important issues. Since Raytheon is
primarily a technology firm, from the engineer’s perspective, the goal is to develop the
latest and greatest radar. This is great for the Program Management as they cannot wait
to develop these technologically advanced products for the customer. Therefore, as in
many other companies, the lack of coordination between Engineering and Manufacturing
results in products that may not be easy to make, driving high costs and quality issues.

On the shop floor, the power is evenly distributed. The Advanced Manufacturing team
and the shop floor workers seem to work well together, each assisting the other as
needed. However, within the Advanced Manufacturing team, two people have a great
deal of power, the director and the senior engineer. The director of Advanced
Manufacturing attends status meetings and is pushing the team to hit its cost and schedule
targets (reduce cost by 50% and average cycle time by 50%). This causes some tension
as there are 2 levels of management under the director that attends these meetings and
they should be the ones pushing change. As for the senior engineer, he has worked on
this product longer than anyone and seems to get the most done. Therefore, most
changes need to be run through him to get his approval before anything moves forward. This seems to fit well within the culture here as Raytheon seems to be a very hierarchical and seniority based company (as mentioned in the Cultural section).

6.3 Cultural Lens

The cultural lens views an organization as a dynamic atmosphere where shared common situations and past traditions develop to shape the organization over time. People take action based on the meanings they assign to situations and the symbolism of particular events help diagnose process within the organization and between new members and the outside world.

The atmosphere is very risk adverse. The company is very conservative when making decisions because many decisions have to go through layers of the hierarchy to get signed off. In addition, a few experts in the field must be consulted before even the smallest decisions could be made. This mentality hinders improvement as people are not willing to try new methods of doing things. It seems that any new idea immediately gets dismissed, not because it is not a good idea, but only because it is new. Working in this environment seems to be a challenged to navigate through since not only are you facing resistance on the floor, you are facing resistance from above.

However, the aversion to change seems to be slowly changing in this organization. The recent realities of increasing competition and rising costs and schedule pressures have people thinking more about continuous improvement than sticking to old ways of thinking. Outsider perspectives are slowly being accepted as a new wave of rapid hiring has occurred recently. This has driven people to start thinking outside the box and pushing harder to try new ideas.
7.0 Recommendations

Typically in aerospace industry, the low volume, high mix product mix amplifies and expands the number of pitfalls and early in the production cycle, where cost and schedule can go out of control very early on in production. However, thinking of new ideas and not relying on tried and true methods may help mitigate ramp issues early on, improving the learning curve and delivering better results in the long run. This will help the team eliminate wasteful actions that are hindering continuous improvement actions.

7.1 Firefighting versus Proactive Issue Resolution

The issues on the shop floor stems from an active firefighting mode that seem to strain the team’s ability to investigate process improvement actions. The team is constantly tackling persistent tactical issues leaving very little time to investigate more long term process improvement. Firefighting mode creates an atmosphere where short term benefits come at the expense long term investigation, which becomes a self-reinforcing loop that detrimentally affects future performance.

To correct this problem, the team should take more time to investigate long term process improvement and separate from the more tactical day to day issues. The team needs to balance the short and long term demands better by relying more on leveraging shop floor personnel and combating the need to do everything. Although this team is in ramp-up mode, where current production needs to ramp-up to the demand target, ample time needs to be spent looking into new production methods that could not only improve future products, but also current production.

7.2 Data-driven Decision Making
Currently, process and product improvement actions were based on hunches and complaints by certain shop floor personnel. For example, the team worked very hard to improve some testing procedures, even though the cycle time and cost savings were minimal. This has not proved to be as effective as these actions were not focused on the issues that would have great impact on the product or process as a whole. In addition, current data collection methods are unreliable and inadequate, where backwards engineering of the data is necessary to complete any form of an analysis to investigate process changes. An example of this is the data analysis completed in this case study. To make a decision about what process to improve, the limited data available had to be creatively fabricated to put it in any form to be analyzed.

Therefore, the data collection system needs to be altered in a way that the proper cost, quality and throughput measurements are collected in real time and presented in form that could be easily analyzed. In addition, the data must be easily separated by cost center, process, unit and function, such that the ability to paint a better picture about the various cost drivers could be completed. Lastly, to drive decisions based on data, the data collection system must be easy to collected and accessible such that the whole process is not cumbersome. If the compiling data is a tedious task, this would be a deterrent towards truly using data as a decision making resource.

However, a cultural shift needs to occur before lean accounting and cost collection can be successful. People need to understand the benefits of collecting accurate data and truly believe that this tool can better drive thinking and decision making. Lack of information inhibits continuous improvement and poorly measured results encourage actions subverting lean management. In addition, people cannot rely on old reporting methods and instead must overcome their resistance to change. This can be difficult, specifically, in cultures where expertise and seniority typically drive decisions. However, without the proper data, decisions could be misguided and potentially more harmful than good.
7.3 Waste Elimination

One of the fundamentals of lean manufacturing is the elimination of waste in the system. The goal of a business enterprise is to create wealth for its owners by creating value for its customers. Therefore, the enterprise must work to eliminate any activity that the customer will not pay for\textsuperscript{21}.

There are seven categories of waste:

- Overproduction
- Motion
- Waiting
- Transportation
- Inventory
- Defects
- Overprocessing

Waste is very prevalent in aerospace manufacturing due to the high-variety, low-mix nature of the industry\textsuperscript{22}. In particular, the coldwall production is plagued by 3 of the 7 categories: motion, waiting and defects. These three sources of waste are likely candidates for future continuous improvement activities to help improve the overall cost, quality and throughput.

7.3.1 Motion

The existence of wasted motion currently on the shop floor is causing the cycle time of the coldwall to be higher than its anticipated target. The development of the automatic deburring method helped correct one source of wasted motion in the plant. The act of manually deburring the metal parts provided very little value for the customer as it required days of labor to complete the task. This project provided an inexpensive and
more consistent means of deburring that will eliminate at least 2 days of cycle time and save thousands of dollars. The result will provide more value to the customer as they will receive their shipments earlier and at a lower cost.

There are many other wasteful motions in the production process. The team should look into how material flows through the shop and investigate how repetitive part transferring could be eliminated. A previous study showed that the part moves almost 2 miles from the start to the finish of the process, mostly carried manually. Each time the part gets moved, the potential of damage increases. In addition, since these parts are very heavy, there is potential for work related injuries every time the part is moved.

In addition, the finding of paperwork for tracking and inspection purposes is wasted effort many deal with on a daily basis. Potentially either a better parts locating system or better information flow among the personnel could help alleviate the stress and effort of finding paperwork to do all the necessary tasks related to production.

7.3.2 Waiting

In three particular areas – deburring, machining, inspection – inventory was piling up waiting to be processed. In the case of deburring, this project should eliminate inventory waiting to be deburred as the new automatic brush deburring will be completed immediately after the CNC machines process the coldwall. However, the CNC machines have stock waiting to be processed as CNC machines are dedicated to specific product lines. This poses a problem since products cannot be processed if the dedicated CNC machine is either occupied or down for maintenance. Therefore, some flexibility needs to be built into the system to help improve the flow of materials through the shop.

Flexibility is the ability to adjust to change or react with little penalty in time, effort, cost and performance. Therefore, the shop should build in more flexibility into the shop to improve the ability to cope with unexpected issues that may arise in the future, such as machine failure or part demand fluctuations. To build in flexibility into the shop, each of
the CNC machines should to be able to process most (if not all) of the parts moving through the shop. This will allow the shop to quickly adjust the production process if demand for a particular part goes down. Since the CNC machines in the shop vary by Original Equipment Manufacturer (OEM), vintage and style (horizontal versus vertical), programs should be written for the various CNC machines to produce the different coldwalls. In addition, clamps and spacers used for the various coldwalls should be fabricated for the different CNC machines. Lastly, the operators can added another level of flexibility by cross training on all of the duties required to operate the shop. Therefore, shop floor personnel should be cross-trained on the task required to set-up and operate the various CNC machines for processing many parts produced in the shop.

In the case of automatic deburring, different programs were written for the two types of machines that produce the coldwall. This allowed the plant to be able to deburr the coldwall on any of the CNC machines that produce the coldwall. Otherwise the benefits of automatic deburring would not be fully realized as the operator would have to remove the coldwall from one machine and setup a different machine to deburr the part.

Increasing flexibility in the shop can also be used to reduce work in progress (WIP) inventory and therefore reduce the amount of stock produced at any given time. If the parts are not waiting as long to be processed, the amount of WIP could be reduced as a part can move more freely through the shop and a queue will not build up in front of processing stations. In addition, improving flexibility can reduce set-up times, which will improve throughput through the shop. Therefore, reducing waiting by adding flexibility will not only improve overall cycle time, but it can also reduce in process inventory and the cost of producing more than necessary.

**7.3.3 Defects**

Current production is plagued with defects, with the coldwall having almost a zero first time through delivery rate. The reason for this is leaks and dimensional tolerance issues
that occur as a result of a design that is difficult to manufacture and design flaws inherent in the manufacturing process. For example, as a result of the brazing, the interface between the metal layers is porous. Many leaks are occurring because of this inherently porous interface. The effort undertaken to fix these defects makes the case for more coordination between engineering and manufacturing to resolve these known manufacturing issues upfront in the design process. If the proper investigation into new and innovative welding methods could be used to manufacture this product, the likelihood of these issues occurring would reduce.
8.0 Conclusion

The methods used in this case are not groundbreaking by any means. However, this case study provides another example of how a product in ramp-up could easily get out of control if the organization is not focusing their efforts on what will make large impact to the bottom line. If the team can be organized such that firefighting is not the norm and continuous improvement and proactive process re-engineering can have greater focus, then very simple process improvements, such as this new deburring method, could be investigated and implemented with excellent results. In addition, not having a data-driven decision making process can hinder continuous improvement by not focusing efforts that have a direct and immediate impact on the bottom line. Lastly, Design for Manufacturing and thinking Lean by eliminating waste early on in the production cycle can help resolve issues before cost over runs and schedule delays spiral out of control. These efforts are painful, but a more proactive, data-driven approach to continuous improvement can save time, money and heartache in the long run.
9.0 Bibliography


3 www.raytheon.com


11 manufacturing.stanford.edu/processes/Deburring.pdf

12 www.pfonline.com/articles/070303.html


15 www.weilercorp.com

16 Carroll, John S. “Introduction to Organizational Analysis: The Three Lenses.” Massachusetts Institute of Technology Sloan School of Management.


