LINE COORDINATION IN A RAPID CHANGE, HIGH VOLUME ENVIRONMENT

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ABSTRACT

Raytheon – Integrated Defense Systems (IDS) manufactures surface radars. In the past, Raytheon's Andover plant was primarily a systems integration facility receiving subassemblies from other sources to assemble the radars. Hence for a long time, building surface radars in low volume had been the norm. However, since the last few years the plant also has been producing some of these subassemblies in high volume. Due to this, the facility had to transition from a predominantly low volume manufacturing environment to one that includes high volume assembly lines.

This thesis examines the challenges that arose due to the transition from a low volume to a high volume manufacturing environment. One of the major problems examined was throughput variability on a high volume assembly line. It has been determined that throughput variability can be reduced by achieving line coordination; i.e. "balance in the flow across the assembly line".

This thesis emphasizes the importance of effective execution of the production plan to reduce throughput variability. It focuses on three key areas that needed improvement – Culture, Manufacturing Practices and Business Systems. The thesis includes improvements implemented to achieve line coordination.

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1 INTRODUCTION

1.1 Raytheon Company

Raytheon Company is an industry leader in defense and government electronics, space, information technology, business aviation and special mission aircraft[1]. The company's vision is to be the most admired defense and aerospace systems supplier through world-class people and technology. To achieve this vision, Raytheon divided its business into four strategic business areas: Precision Engagement weapons, Missile Defense, Homeland Security and Intelligence, Surveillance and Reconnaissance. The company, headquartered in Waltham, MA, generated $18.1 billion in revenues in 2003 and employs 78,000 people worldwide. The technologies needed to achieve the Ballistic Missile Defense System mission — radars, sensors, target discrimination systems, guidance and control systems — are among Raytheon's core strengths.

1.2 Raytheon - Integrated Defense Systems (IDS)

Raytheon-IDS (formerly Raytheon Electronic Systems), a business within Raytheon Company, is a world leader in Missile defense. The company's "One Company" focus and commitment to its customers makes it one of the defense industry's leading missile systems integration businesses. Some of IDS's well known products are Ballistic Missile Early Warning System (BMEWS) Radars, the HAWK/AMRAAM Air Defense System and the Patriot Missile System. Headquartered in Tewksbury, MA, IDS generates approximately $3.1 billion in revenues and employs more than 11,000 people.

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[1] www.raytheon.com

IDS's main manufacturing facility in Andover, MA, is a major surface radar and world class commodity manufacturing center. This manufacturing facility reorganized in Nov 2002, around the customer into Value Streams. A value stream is a group of people— design engineers, manufacturing engineers, production control staff, supply chain people - that are directly linked to a particular customer[2]. The value streams manufacture products not only for the Andover facility but also for the entire Raytheon organization.

The work for this thesis was conducted in the Microwave Value Stream.

1.3 Microwave Value Stream

The microwave value stream produces precision high volume microwave subassemblies for the Phased Array Radars required for THAAD, BMDS, SBX and other ballistic missile defense programs. The radars that use these subassemblies are assembled by the Integration value stream. Further information on these programs can be obtained at Raytheon's website[3].

The microwave value stream is organized along various product based cells and each cell is led by a Cell Leader (Manufacturing Manager), reporting to the Value Stream Manager. The value stream is managed by the Value Stream Manager who reports to the Director of Manufacturing (Figure 1). The Value Stream Manager also reports to Integrated Product Team (IPT) Leaders responsible for various programs. The organization is set up in such a way that the Integrated Product Teams reporting to the Program Managers focus on customers whereas the Value Stream Managers and the Director of Manufacturing focus on execution.

[2] Shoot for the Moon - The Manufacturer, July 2002 Vol 2 Issue 7
[3] www.raytheon.com

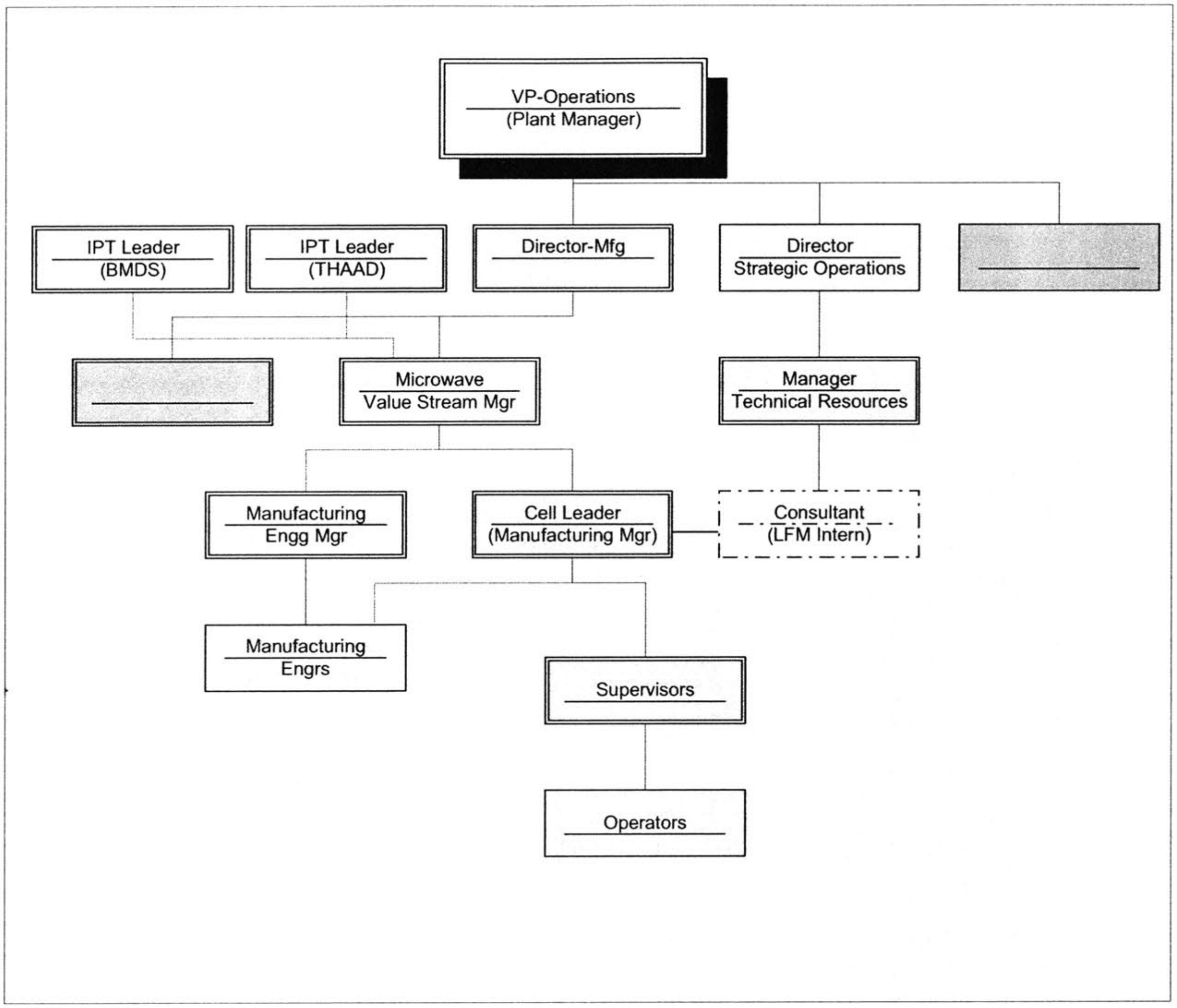

Figure 1: Microwave Value Stream Organization Chart

1.4 The Product

At the time of this internship, the microwave value stream was building antenna subassemblies for a surface radar system. This radar system is part of a strong, coordinated defense against incoming theater ballistic missiles. The surface radar is a large phased array radar that contains around 20,000 identical transmit/receive microwave subassemblies as part of the antenna. A few of these microwave subassemblies are packaged into an antenna subassembly and about 3000 such antenna subassemblies are then placed in the array aperture of the surface radar structure.

The microwave value stream assembles the precision microwave antenna subassemblies. The parts to build the antenna subassemblies are sourced both from internal and external suppliers. The finished subassemblies are delivered to the Systems Integration and Test group that assembles these subassemblies into the array structure to populate the antenna aperture. This radar is then tested and delivered to the customer.

The research for this thesis was conducted in the final assembly line of this antenna subassembly.

1.5 Thesis Overview

Chapter 1 provides a brief introduction to the company and the division where the research was conducted for this thesis. The motivation for this project is also discussed in this chapter.

Chapter 2 is an overview of concepts and terms used in the thesis.

Chapter 3 presents the background to provide the reader with an understanding of the environment the research was conducted in, and defines the problem statement.

Chapter 4 covers the analysis conducted to identify the factors contributing to the problem.

Chapter 5 is a detailed description of the implementation steps undertaken to resolve the problem.

Chapter 6 covers the challenges faced during the internship.

Chapter 7 presents conclusions from the internship.

Chapter 8 highlights future projects identified for further research.

1.6 Project Motivation

The internship was jointly sponsored by the Strategic Operations group and the Manufacturing/Engineering group within IDS. When Raytheon won the contract to build the Surface Radar, the Andover plant had to compete with other Raytheon facilities and external subcontractors to win the manufacturing contract to build the subassemblies and integrate and test the Surface Radar. There were a lot of skeptics in the company who felt that Andover's core competency was systems integration and not component manufacturing. They believed that Andover did not have the expertise to manufacture the required parts, mainly because it had been a systems integration facility in the past. They believed that the components/sub-assemblies could be manufactured in a more cost effective manner by other Raytheon facilities. The Strategic Operations group played an important role in highlighting Andover's manufacturing capabilities, bringing the much needed work to this plant and orchestrating its successful integration into what is now called Raytheon's Air Defense Center (IADC) in Andover, MA.

In addition, Raytheon has multiple other contracts to build similar radar systems with deliveries in 2004, 2005 and 2006. Successful delivery of the product for this program helps grow continued future business to IDS and IADC at Andover. However, in June 2003 (the time of the internship), this antenna subassembly line was facing many challenges, some of which were technical. The production process was not under control. The major task of the internship, as defined by the management, was to investigate and ensure that the assembly line would be equipped with the right processes to deliver the product on schedule when the technical problems were fixed. Therefore, it was important to implement process improvements, to effectively accomplish high volume component manufacturing.

1.7 Project Approach

The internship started by taking a big picture view of the antenna subassembly's final assembly line processes. Following this, the project plan identifying important milestones (as shown in Figure 2), was prepared within the first two weeks of the project.

The project was split up into multiple phases. The initial phase focused on gathering data to identify the primary problem that needed to be solved. The first few weeks were spent in discussions with key stakeholders - Quality Assurance and Control groups, Design Engineering, Process Engineering and Manufacturing Engineering groups - to identify and document the issues. Most of the information was collected through one-on-one interviews and brainstorming sessions. This helped in understanding multiple perspectives.

The next phase was the analysis phase to identify the areas that needed improvement. The implementation phase included developing and implementing recommendations and tools based on the analysis and literature survey.

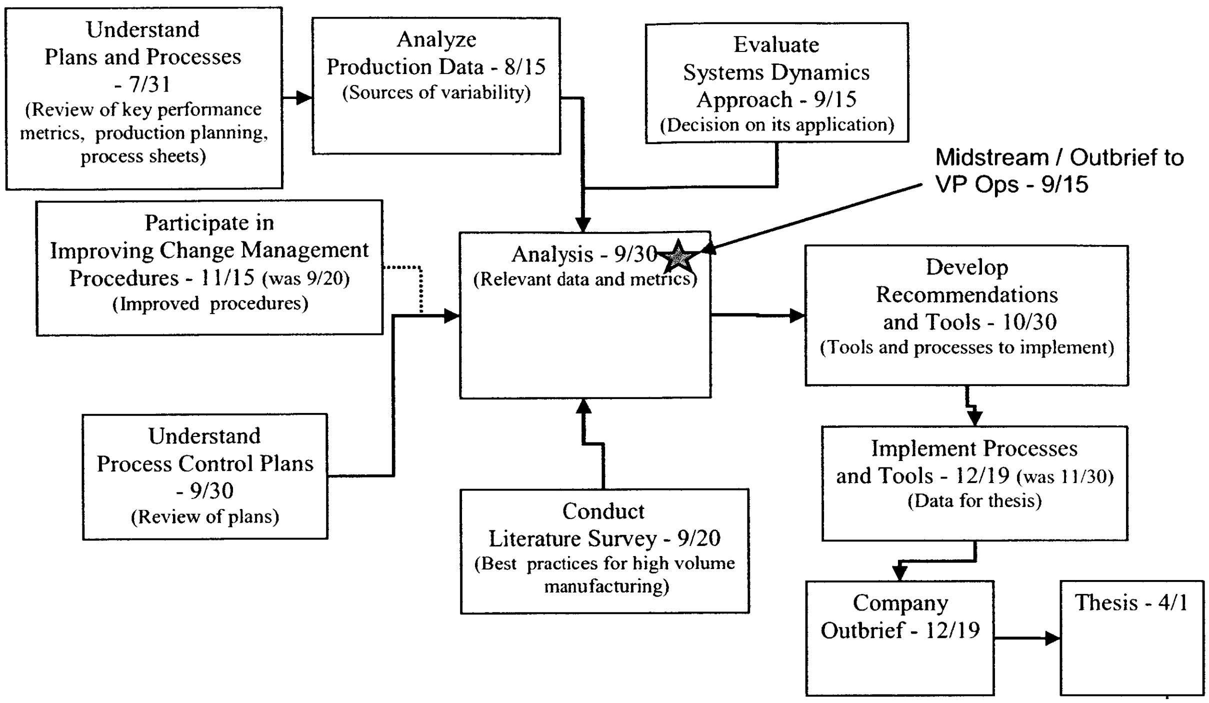

Figure 2: The Project Plan

2 LITERATURE REVIEW

The focus of the research was to balance the production manufacturing flow, through improved line management. This section describes some of the relevant concepts and terms adopted in the process improvements.

2.1 Lean Manufacturing

Lean Manufacturing is a systematic approach to achieve customer satisfaction, through continuous improvement to create value by eliminating waste. One of the reasons Lean manufacturing has been quite popular is because it provides processes to add value by focusing on eliminating waste and inefficiency, thereby freeing up resources needed elsewhere in the business. However, Lean techniques typically need augmentation to optimize their effectiveness. This thesis addresses such a situation.

The intent of this internship was not to implement Lean manufacturing, but to use some of the Lean tools to reduce throughput variability by achieving line coordination.

In *Lean Thinking*[4], Womack and Jones state five principles for Lean manufacturing:

1. Value – It is defined as "Value for the customer". i.e., value is what the customer is willing to pay for. To identify value and eliminate waste, every one in the system has to understand who the customer is and what the customer wants.
2. Value Stream – A Value Stream is the complete set of activities required to deliver a product or service. The concept of value stream requires visibility into other

[4] Womack, James P. and Jones, Daniel T.; *Lean Thinking*, Simon & Schuster, New York, 1996

organizations – thus enabling the sharing of best practices, eliminating non-value added activities.

3. Flow – Once the value stream is identified, the product has to flow through the value stream. Flow enables the activities in the value stream to be connected and hence communicate with each other.
4. Pull – Instead of pushing product, Pull means that a product or service is delivered only when the customer pulls for it. In a production environment, this means that no upstream operation produces a part until its downstream operation asks for it.
5. Perfection – This last principle highlights the importance of transformation through continuous improvement. Once an improvement opportunity is identified, the process should go through the Plan-Do-Check-Act (PDCA) cycle[5] to strive for perfection.

The Lean approach is to apply these principles to identify and eliminate waste. Waste is defined as any non-value added activity (activity the customer is not paying for e.g. material handling, inspection).

The following are some of the tools used for Lean manufacturing. Only the tools that are relevant to or implemented in this project are discussed here. A detailed discussion of these and other Lean tools can be found in *Lean Thinking*[6].

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[5] Shiba, Shoji and Walden, David; *Four Practical Revolutions in Management: Systems for Creating Unique Organizational Capability*, Productivity Press, Portland, Oregon, 2001

[6] Womack, James P. and Jones, Daniel T.; *Lean Thinking*, Simon & Schuster, New York, 1996

2.1.1 Takt Time

Takt in German means a conductor's baton. In production, Takt time is used like a baton to synchronize the production rate to the customer delivery rate. This ensures that customer demand is met on time. Takt time is defined as:

Takt time = Available production Time/Customer delivery rate

For this project, available production time in a day was 7 ½ hours. This is equal to 450 minutes. The delivery rate objective was 30 units per day. Therefore, Takt time = 450/30 = 15 minutes. This implies that the line had to deliver a unit every 15 minutes.

2.1.2 Standardized Work

Workers in a Lean cell are teams that are required to perform all the operations in the cell. Standardized work makes this possible so that the team follows the same approach every time, while providing stability to the process. This makes it possible to accurately measure and plan throughput and also to continuously improve the operation methodology. Standardized work also enables the production process to deliver the product according to the Takt time.

2.1.3 5S/Workplace Organization

5S is a tool for workplace organization. The 5S are Sort, Store, Shine, Standardize and Sustain. This tool enables better teamwork through self-discipline. Sort and Store require identifying the equipment and tools needed and storing these in the right places. Shine forces the team to keep the equipment, tools and hence the workplace clean to provide a better work environment. Standardize and Sustain are for defining and standardizing procedures for various activities in the cell. This facilitates sharing of the right information among team members.

Raytheon extends the standard 5S chart to include Safety as the sixth parameter, to ensure that the workplace is also scored in terms of safety. Refer to Exhibit A for Raytheon's 6S checklist.

2.1.4 Visual Control

In a Lean cell, the workers are a part of cross-trained teams. Workers have to feel empowered for continuous improvement and team work. This is possible only when they are aligned with the organization's goals and know how their efforts are contributing to these goals.

In the LFM thesis[7], *Implementation of a System of Visual Indicators at Intel's D2 Fab*, Smith highlights that the traditional manufacturing systems' view suggests that manufacturing systems require the following three inputs: capital, material and labor, to produce one output: the product. He argues that this view is incomplete because it does not consider an equally important input – information. Information puts the above three inputs together to provide performance indicators to make manufacturing systems more efficient. Visual controls provide the means to share information to produce the product.

2.1.5 Single Piece Flow

In a manufacturing line with Single Piece Flow, the parts flow through the line one at a time, as opposed to in a batch. This is more efficient because parts don't wait in queue to be batched to move to the next operation. Single Piece Flow enables the product to flow through the line without interruptions, thus achieving Lean's third principle (Flow).

Single Piece Flow is especially efficient for this assembly line, because the line produced only one type of product. Therefore, no changeovers or setups were required from one part to another.

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[7] Smith, Erik S.; *Implementation of a System of Visual Indicators at Intel's D2 Fab*, LFM Thesis, June 2003

2.1.6 Lead Time

Lead time is the amount of time between releasing material to the floor and delivering the finished goods to the customer. Lead time includes both the value added time (actual processing of the part) and the non-value added time (time a part spends on the floor waiting to be processed). Application of relevant Lean principles helps reduce non-value added time, hence reducing lead time.

2.1.7 Dynamic Cycle Time

Dynamic cycle time is a statistically probable value for predicting the lead time assuming an unchanged environment. Dynamic cycle time is an important aspect in production because it helps in identifying the WIP levels for a required lead time and throughput, based on Little's law,

Dynamic Cycle Time = WIP/Throughput

2.2 Theory of Constraints

Theory of constraints is a management philosophy based on improving an organizations performance by identifying and managing its constraints. A constraint can be either a process or a machine or any other resource that constraints the organization from moving forward to achieve its goal. This concept was first introduced in *The Goal*[8] mainly to improve output in factories with production delays. Managing constraints means that it does not matter if the outputs from individual processes or resources are improved unless the bottleneck (slowest resource) is improved because the output of the system is driven by the output of its bottleneck.

[8] Goldratt, Eliyahu M. and Cox, Jeff ; *The Goal: A Process of Ongoing Improvement*, North River Press, New York, 1986

2.3 Six Sigma

Six Sigma is a statistical measure of processes to reduce service or product failures. Six Sigma was first introduced to Raytheon in 1998 to establish a company-wide culture to maintain superior quality while growing the business. The methodology was developed by benchmarking other companies and leveraging internal best practices.

Raytheon Six Sigma™ launched in 1999 is more than quantitative statistical manufacturing quality control. It encompasses every aspect of company's work to push the decision making to lower levels with a fact based problem solving approach. Raytheon qualifies employees at two levels, Specialists ("Green Belts") and Experts ("Black Belts").

Raytheon is a stakeholder and co-director of the Lean Aerospace Initiative (LAI)[9] at MIT, but does not have a company-wide Lean initiative. Raytheon Six Sigma™ processes and tools cover most of the Lean implementation opportunities and techniques. Any process improvements including Lean initiatives are implemented by employees as Raytheon Six Sigma™ projects.

[9] http://lean.mit.edu

3 BACKGROUND

3.1 The Environment

This section describes the operational environment of the line at the time of the research.

3.1.1 Tight Schedules

The contracts with the customer stipulate that Raytheon deliver the radars to the customer according to a predefined schedule. These contracts operate under heavy penalties for missing schedules. Raytheon will also receive a certain percentage of the contract value as bonus, if all the required cost, quality and schedule objectives are achieved. These reasons make it very important for all the value streams and suppliers to deliver the required quality parts on time and within budget to build, integrate and test the radar.

3.1.2 Low Volume Culture

The MRP system determined the required throughput rates for the final assembly line, based on these promised schedules. Therefore, the demand was known and was more or less constant on a daily basis. However, if the daily rates were not met for a certain period, the production requirement increased to make up for the backlog. The large phased array radars that the Andover plant typically manufactures are built in low volume, a few per year. In contrast, this particular antenna subassembly target production rate was 150 to 300 per week. This was a relatively high volume for this plant. Because the plant was used to making parts in low volume, the *culture and hence the processes and tools are not geared for high volume manufacturing.*

3.1.3 Large WIP

The production for this subassembly began in November 2002. By the start of the internship in June 2003, no parts were delivered to the customer due to various technical problems in production. In July 2003, there were about 2000 parts in WIP, while the contract was to deliver a little more than 3000 parts. The material was released to the floor according to the production plan and the assembly line continued to process parts through the initial assembly steps. Most of the parts in the WIP were in the input buffers of the operations facing technical problems. The first batch of parts (about 50 parts) was delivered to the customer in late July 2003.

3.1.4 Lean Manufacturing Initiative

The Andover plant had adopted a Raytheon Six Sigma™ project to implement Lean manufacturing. The plant was organized into Value Streams. The manufacturing areas in the Microwave Value Stream were laid out as product based cells. The cell layout is an efficient layout for high volume manufacturing, as can be seen by its application in high volume assembly lines like in the automobile industry. The line operated as a Single Piece Flow line. This allowed for the parts to be worked on as soon as they were processed by the previous operation, instead of waiting to be batched.

The Lean principles were however not implemented across the entire value stream. The microwave value stream did not operate as a true "Value Stream" in terms of sharing information with suppliers and customers. The assembly line was indeed designed based on Lean principles, for the initial process when the production for this product started. However, due to the technical issues with the product, the process changed significantly after the layout was designed and many operations were either added or moved in the process. This resulted in a layout that did not flow efficiently from the first operation to the last operation. Though the layout of the assembly line was designed based on Lean principles, the floor layout had become sub optimized and less efficient than originally envisioned.

3.1.5 The Assembly Line

The assembly line was designed to make 30 parts per day, in two shifts. The process was mostly manual, consisting of about 20 operations including thermal and environmental testing. Some of these operations required highly skilled labor including the use of highly specialized tools and equipment.

The operators working on the line were unionized. The line was supervised by two foremen who reported to the Cell Leader. Two manufacturing engineers were available on the floor to resolve engineering issues. The operators followed work instructions available online via a monitor at every station. The manufacturing engineers were responsible for keeping the work instructions up- to-date, incorporating the new process and change improvements.

3.1.6 Technical Issues

At the start of the internship, the manufacturing line had been missing schedules and facing many technical challenges. The main challenge was the Ribbon Bonding operation. Ribbon bonding is high yield interconnect process that uses heat and ultrasonic energy to form a metallurgical bond. This operation was unreliable and produced poor first pass and test yields, resulting in 100% rework. A team of expert engineers was already in place to address the problems with this operation. This team also included another LFM intern whose internship was to bring this operation under control[10]. A snapshot analysis of the 700 parts in the WIP made it obvious that this was the primary bottleneck.

[10] Balazs, Brett; *Visual Tools: Controlling and Improving the Ribbon Bond Process*, LFM Thesis, June 2004

The other challenge was the misalignment of the components after Environmental Test. This was mainly due to the design being not robust enough for high volume manufacturing. Another team of engineers addressed this problem.

The third problem was an important quality problem due to RF leakage (ripple problem). This was noticed after processing hundreds of units. This problem reduced the yield considerably. The reason for this was inadequate testing during proof of manufacturing. In addition, the design modeling and simulation tools were inadequate to predict and detect this phenomenon. This problem was addressed by introducing highly manual-intensive rework.

The situation was further made difficult due to a culture clash[11] between design and manufacturing groups. The design group always wanted more data to find the root cause for the problems during manufacturing. However, because of the technical problems during production, Manufacturing did not have enough resources to take the extra measurements necessary to provide the ever increasing volumes of data. Moreover, some of the design decisions resulted in complicated manufacturing processes making it more difficult to gather the required data.

For the purpose of this internship, it was assumed that the technical problems would be solved in the near future. As of three months into the internship, most of the product/process technical issues had been solved.

3.1.7 Shop Floor Data Management

The assembly line used a software system called Shop Floor Data Manager (SFDM). SFDM is a floor control and non-conformance tracking software tool. Operators logged their work into this system. This system provided all the operational and financial metrics. Analysis of data from this

[11] Engineering review meetings at Raytheon

system was laborious and often error prone. Extensive investigation showed that the process engineering group that set up the system did not completely understand the high volume manufacturing requirements. A combination of incorrect implementation of SFDM and insufficient user training resulted in people entering a lot of data into the system that could not be used for any decision making. In addition, the management and the operators spent a significant amount of time manually reconciling the SFDM data with the status on the floor.

In summary, the following issues directly impacted the throughput rates:

- The operators were unaware of the daily goals and other metrics.
- The management did not have a catch-up plan to compensate for the backlog.
- The foremen were often caught by surprise with frequent product/process design changes.
- There was a large amount of WIP on the floor because there was no consensus on the daily work plan.
- The testing during proof of manufacturing was insufficient – a view shared by both the design and manufacturing engineering groups
- A significant amount of time was spent on manual collection of data on the floor in spite of having the SFDM system.
- There was a lot of variability in the daily throughput.

3.2 Problem Statement

The radar subassembly line was missing customer delivery schedules due to variable daily production rates. The objective of this internship was to achieve line coordination to deliver the planned throughput.

In a well coordinated line, each operation consistently produces only the units required to meet the day's throughput goals. That is, the flow through the line is balanced. This improves planning and reduces variability, thus reducing inventory buffers. Reduction in variability also reduces the WIP. Flow balancing also improves worker efficiency because the operation standard time is matched to the Takt time[12].

[12] Czarnecki, Hank; and Loyd, Nicholas; *Simulation of Lean Assembly Line for High Volume Manufacturing*

4 ANALYSIS

This phase of the internship focused on the analysis of the data and processes to identify the sources of throughput variability and to determine the root cause for the problems.

4.1 Sources of Variability

4.1.1 Cause and Effect Analysis

The numerous interviews with shop floor managers, design and manufacturing engineers, quality personnel and operators helped in gaining multiple opinions and perspectives for the sources of throughput variability. The following fishbone diagram (Figure 3) categorizes these sources. The highlighted boxes represent those attributes targeted during the course of this internship.

Some of the key sources for throughput variability are:

Culture: Both the manufacturing and design groups were accustomed to making parts in low volumes. Therefore, the procedures and long term plans did not support high volume manufacturing. The employees did not understand the goals and the plans to achieve these goals. "Problem of the Day" was given far more importance than long term plans, fostering a fire-fighting environment.

Manufacturing: The line was facing technical problems. There was no framework to manage bottlenecks once the technical problems were solved. The standard work instructions changed frequently due to design and process improvements. The supervisors were often unaware of these upcoming changes.

Business systems: There was no data integrity between SFDM data and the hardware on the floor. People spent a significant amount of non-value added time accessing and correcting SFDM data.

Machines: The ribbon bond machine was not producing at expected yields. This was the bottleneck in the line. There was only one test machine for two different test operations. This machine was shared with other product lines. There was no predetermined schedule on the availability of this test machine.

Design: The design of the part was not robust enough for high volume manufacturing. It was too late to change the design for this program because some of the key components were already sourced from the suppliers.

Material: The line was often starved due to lack of quality material from the suppliers, both internal and external.

Training: Training was inadequate to accommodate the continual introduction of new processes as part of rework.

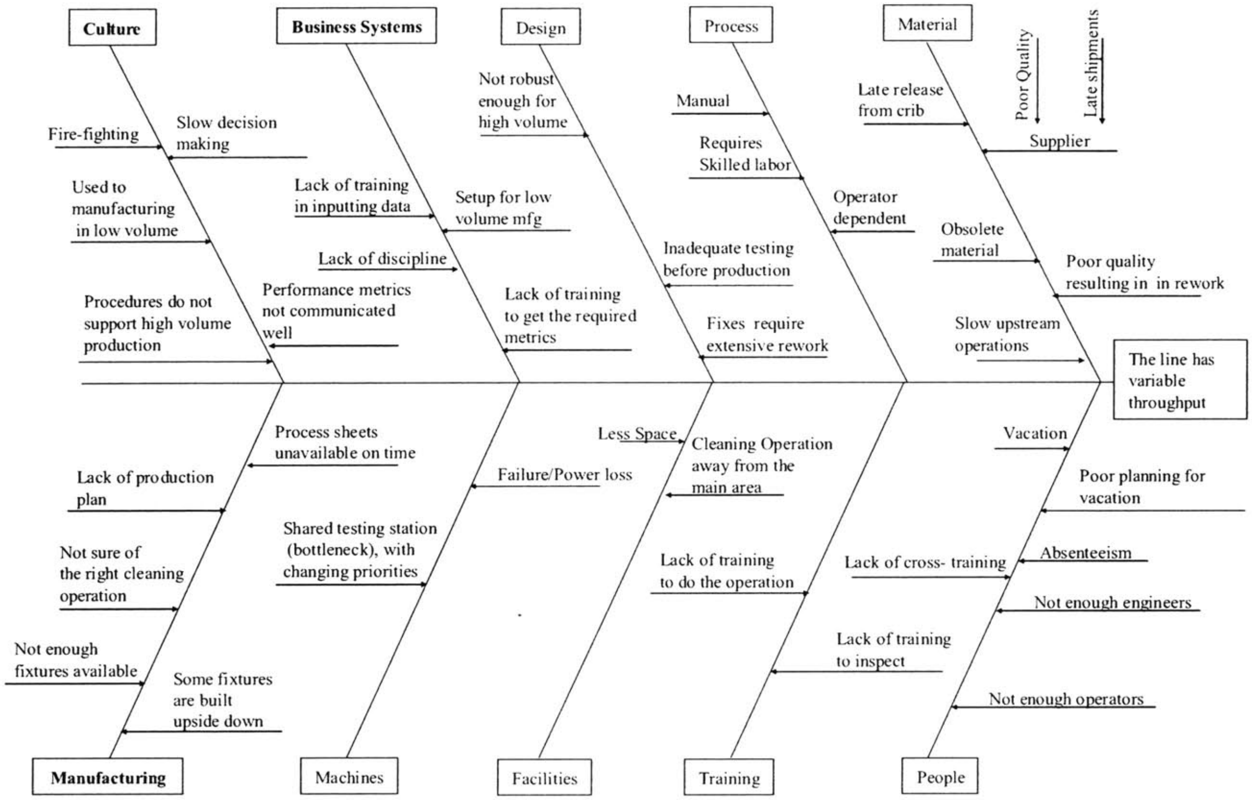

Figure 3: Sources of Throughput Variability

Based on these key findings, the internship narrowed down the focus to the three areas highlighted in figure 3, for further analysis and subsequent improvements. This was done to effectively address the issues and make a difference with sustainable improvements in the short duration of six months of the internship.

4.1.2 Root Cause Analysis

The sources of throughput variability (identified in Figure 3) were modeled as causal loops (Figure 4) to identify the root cause for the problem.

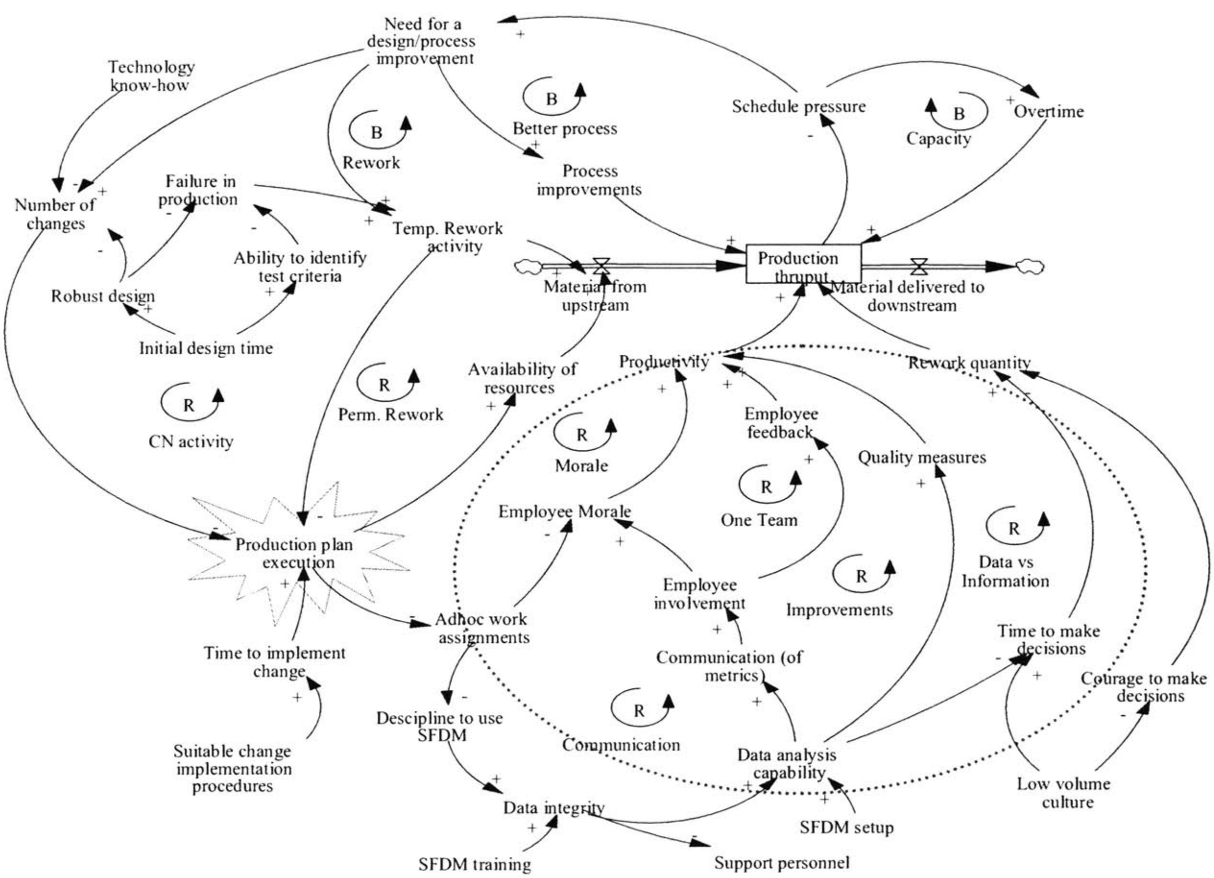

Figure 4: Systems Dynamics Model Highlighting the Root Cause and the Variables Affected by the Root Cause

The above systems dynamics model has three types of variables: stocks, flows and auxiliaries. Stocks are variables that accumulate over time and are shown as rectangles. "Production thruput" is the stock variable in the above diagram. Clouds in the diagram represent stocks that are out of scope (boundaries) for the system. Flows are rates at which material enters or leaves a stock. These are represented by pipes (double arrows) with valves. The arrow shows the direction of the flow. In this diagram, "Material from upstream" is the inflow and "Material delivered to downstream" is the outflow. Auxiliaries are variables that are used to calculate the values of inflows and outflows. These do not have a graphical representation and are shown by the variable name. The single arrows represent the causality between a pair of auxiliaries in the system. A "+" sign at the arrow head implies that the variables connected by the arrow move in the same direction. For e.g., the arrow connecting "Schedule pressure" and "Need for design/process improvement" indicates that as "Schedule pressure" increases, "Need for design/process improvement" also increases. Similarly, A "-" sign at the arrow head implies that the variables connected by the arrow move in opposite directions. For instance, the arrow connecting "Number of changes" and "Production plan execution" indicates that as "Number of changes" increases, "Production plan execution" decreases. For more information on the use of causal loops for systems dynamics modeling, please refer to Business Dynamics[13].

The model has two types of loops: Reinforcing loops (R) and Balancing loops (B). Following is an explanation for two of these loops to illustrate reading the above diagram.

Balancing loop: In the "Better Process" loop, as the "Production thruput" decreases, the "Schedule pressure" increases, thus increasing the "Need for a design/process improvement". This in turn increases the number of "Process improvements" which will increase the "Production thruput". Therefore this balancing loop balances the throughput via process improvements.

Reinforcing loop: The "Morale" loop shows that, as the "Production thruput" decreases, the "Schedule pressure" increases, thus increasing the "Need for a design/process improvement". This in turn increases the "Number of changes". As the "Number of changes" increase, the ability for "Production plan execution" decreases. Because of this, "Adhoc work assignments"

[13] Sterman, John D.; *Business Dynamics: Systems Thinking and Modeling for a Complex World*, Irwin/McGraw-Hill,

increase which results in reducing the "Employee morale". Lower "Employee morale" results in lower "Productivity", thus decreasing the "Production thruput". Therefore, this reinforcing loop reinforces or further decreases the production throughput.

The model highlights that there are a lot of these reinforcing loops that have a high impact on "Production thruput". It is important to make sure that these act in a positive way, to improve the throughput. As can be seen in the model, all these loops originate from "Production plan execution", i.e., the ability to execute the production plan well would drive these loops to further increase the throughput. Due to this, it is important to analyze and control the parameters that effect the execution of production plan.

The above analysis concluded that the root cause for throughput variability was that *the assembly line was unable to effectively execute the production plan.*

The following situation analysis explains in detail, the factors leading to these sources of throughput variability.

4.2 Situation Analysis

The situation analysis was conducted along the following parameters:

4.2.1 Integrated Product Team (IPT)

The program this radar subassembly belonged to, was the first where Raytheon-IDS was attempting a product centric program management using IPTs. Each IPT was led by the IPT lead. The IPT members included representatives from various groups like design engineering, manufacturing, materials and quality. The IPT organization facilitated cross-functional communication, while taking advantage of functional expertise of the representatives, thus enabling improved quality and reduced cycle time. On the whole, using this program management approach proved useful and was being carried over to other programs[14].

While the IPT helped with providing cross-functional input for designing the parts, the manufacturing process development did not follow a similar peer review process. The tool design and other manufacturing aspects were not fully validated by a cross-functional team[15]. This resulted in fixturing errors and several other inefficient manufacturing processes, as identified in the fishbone diagram (Figure 3).

4.2.2 Design Engineering

There was an intense cost and schedule pressure right from the inception of the program. The First Article Verification for manufacturing was done in September 2002, (though a later one done in April 2003 proved to be more useful). This resulted in a design that was still not robust enough for high volume manufacturing.

Design engineering also operates in a low volume culture. They often revisited decisions made in the past and introduced manual intensive rework to fix the design. Fixes introduced as temporary ones became permanent solutions. At the start of the internship the design problems produced unplanned rework and frequent change notices. This put the line in a constant fire-fighting mode, leaving almost no time for long term planning or process improvements. Even after the bulk of the design problems had been addressed, the line seemed to be operating in the same fire-fighting mode.

This can be made clear with the following examples:

[14] Conversations with the IPT Lead
[15] Conversations with Design Engineer

To fix the RF leakage problem mentioned in Section 3.1, Design Engineering introduced a rework process. This added three new operations that required highly skilled labor. The operators were not well trained, so the operations took longer than expected. Moreover, the inspectors either passed defective parts or failed good parts, because of a lack of training. Therefore, this process caused a lot of delays. It was not uncommon to starve the assembly line because there was not enough manpower for this rework process. Eventually, the operators did get better at this process and the line was no longer starved, but the extra resources still needed to be maintained.

In another instance, the design engineer assigned to fix the mechanical alignment problem recommended that the best solution was to perform the alignment multiple times, instead of the planned one time alignment. The design engineer's study proved that presenting the part multiple times to the fixture provided good yields because each presentation improved the alignment. However, the design engineer did not seem to consider the 30 minutes it took for each iteration. This would be an effective solution if the parts were manufactured in low volume. But performing these extra iterations on thousands of parts proved to be quite time consuming and expensive. After following this recommended procedure for a few weeks, both the design and manufacturing groups agreed to revise the specifications to avoid these multiple iterations.

The concept of Key Characteristics (KC) introduced by the previous LFM intern[16] was believed to be widely in use. However, the design engineering group used these key characteristics to measure the parts during manufacturing, but not during the design process as intended. The above mechanical alignment problem is an example of not applying the KC concept during design, because there was no data or knowledge if the KCs for the subassembly are delivered

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[16] Lund, Mack R.; *Predicting Manufacturing Performance of New Radar Subassembly Designs*, LFM Thesis, June 2003

from the component KCs. Proper application of KCs during design would have identified these problems much earlier, even before having to manufacture and test them[17].

The research conducted by the LFM intern in 2002[18], discusses the importance of concurrent engineering and the impact of design problems on the "leanability" of the manufacturing system. The Lean techniques are proven to be more effective when the design is mature[19]. These factors make the impact of design engineering an important factor for any process improvement.

4.2.3 Process Flow

In June 2003, the assembly process consisted of 18 operations. However, the work content of the operations and the number of operations often changed, resulting in a process sheet (Standardized Work instructions) that was updated almost every month. This made it very difficult to calculate Standardized Work and plan the production requirements based on Takt time.

Figure 5 shows the process flow diagram for the radar subassembly. This process flow diagram captures the sequence of operations in the general assembly process and may not depict exactly the flow at a given point of time due to the frequent changes in the process.

The raw material was staged in the crib and materials were released to the floor based on the MRP schedule. The parts then went through a few initial assembly operations before the first inspection step. Parts that passed the inspection proceeded to the next assembly steps. Parts that failed inspection were either placed on the Redrack or assigned to a rework operation.

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[17] Conversations with LFM Thesis Advisor Daniel Whitney

[18] Sweitzer, Timothy J.; *A Simulation-Based Concurrent Engineering Approach For Assembly System Design*, LFM Thesis, June 2002

[19] Discussions with Lean experts at Raytheon Advance Product Center, Dallas

After passing the second inspection step, the parts went through cleaning operations before proceeding to the ribbon bond operation. After the ribbon bond operation was successfully completed, the parts went through a few test operations including thermal and environmental tests. Parts that passed these tests proceeded to the final operations in the assembly process. The parts were then delivered to the customer after passing the final inspection.

Input buffers (WIP) were maintained for each of the operations. There were no limits on the sizes of these buffers. WIP for rework was maintained after each of the inspection steps.

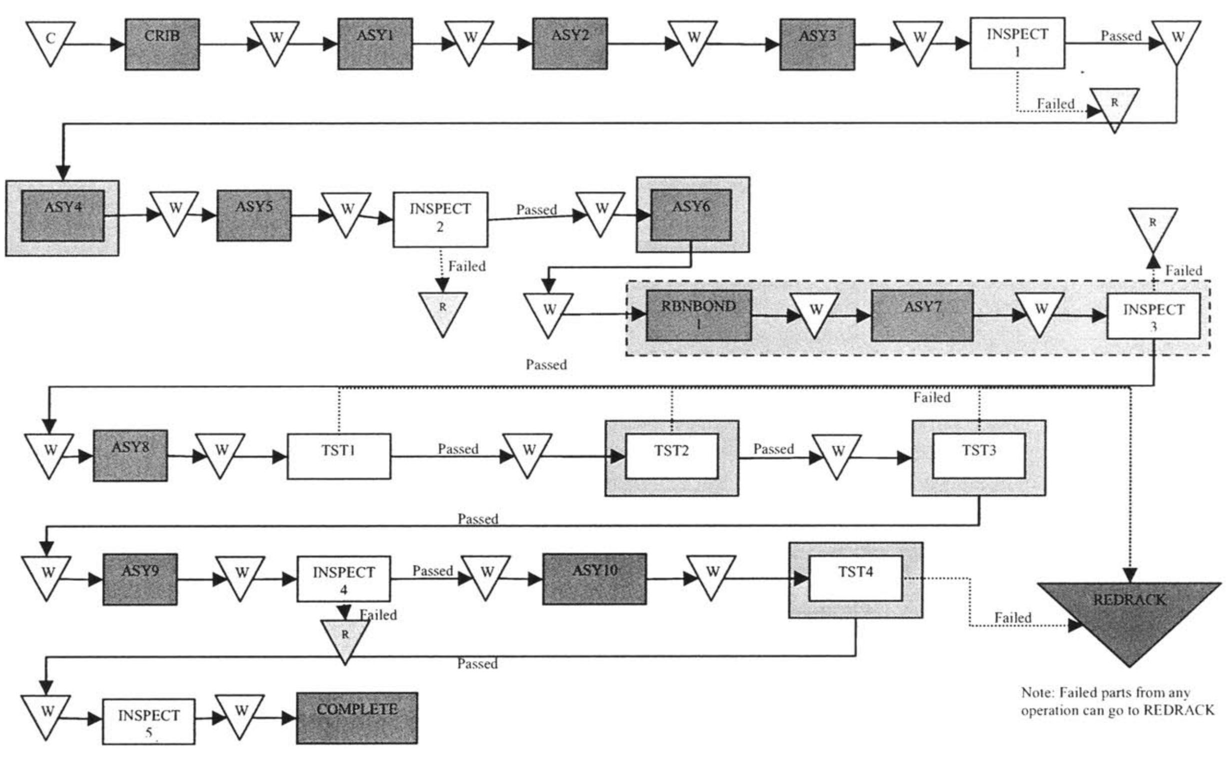

Figure 5: Process Flow for the Antenna Subassembly

The parts were tagged with an SFC number (Shop Floor Control number) that was unique to each part. The operators took parts from the assigned operation's input buffer (WIP), performed the operation and placed them in the input buffer for the next operation.

4.2.4 Process Layout

All the assembly operations were in one area and were visible to each other. The ribbon bonding and related rework operations were in a separate room with glass walls in the same area, making these operations visible to the main assembly area. The test operations including the input buffers for these operations were in a separate room away from the main assembly area. Figure 6 shows the process layout.

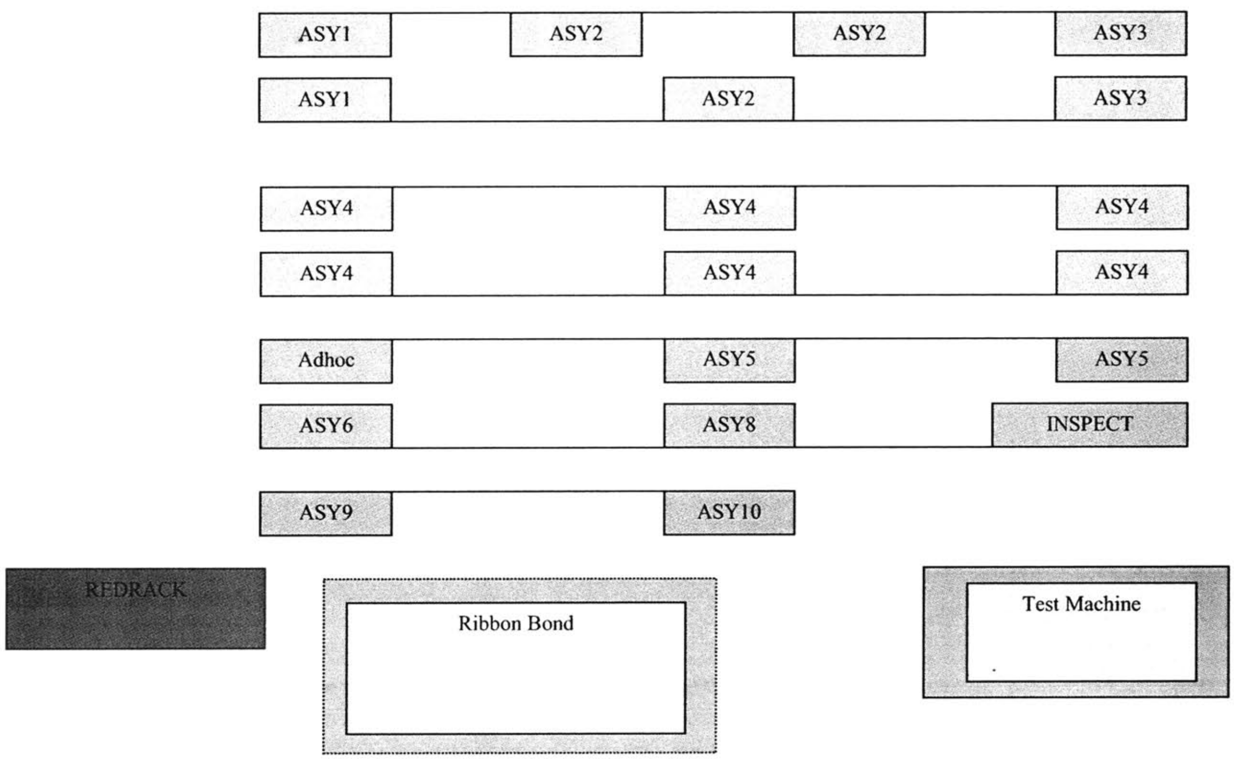

Figure 6: Process Layout of the Antenna Subassembly line

The assembly and inspection operations were all manual. The workstations were designed to perform any of the operations. Though the operations required specific tools, the tools were portable and could be carried to any workstation. This allowed the operations to be performed at different workstations depending on where the operators liked to work and the number of operators working on an operation at a time. The number of workstations for each of the operations was based on the required throughput and the time required for performing the operation.

Example: ASY1 takes 45 minutes and ASY3 takes 80 minutes. To produce 30 parts per day, with a takt time of 15 minutes:

Number of operators required for ASY1 = 45/15 = 3. That is, ASY1 requires 3 workstations.

Number of operators required for ASY3 = 80/15 = 5.3. That is, ASY1 requires 5 to 6 workstations.

In practice, the number of workstations used for a particular operation also changed based on the availability of operators on first and second shifts.

4.2.5 Production Planning

The production rates were planned by the MRP system. MRP systems are good for planning and hence push the product through the system[20] to control the throughput. The material was released to the floor according to the production plan. There was no control over the WIP because the MRP system did not take into account the current WIP on the floor to release the material. The priority of the work to be performed was solely based on the foremen's judgment. Though the

[20] Hopp, Wallace J. and Spearman, Mark L.; *Factory Physics, Foundations of Manufacturing Management*, Irwin/McGraw-Hill, Boston, MA, 1996

Cell Leader had a manufacturing scorecard, neither the foremen nor the operators were aware of its existence or usage. There was no consensus between the first and second shift foremen on the daily production goals. The following example illustrates this problem:

The following table shows the production throughput on July 24, 2003.

Date	**Operation**	**Throughput**
7/24/2003	ASY1	55
7/24/2003	ASY2	166
7/24/2003	ASY3	65
7/24/2003	ASY4	18
7/24/2003	ASY5	11

At one point during the day, six operators worked on ASY3. The next day 72 parts were in the input buffer for ASY4 (output from ASY3). But, no trained operator was available to work on ASY4 due to planned and unplanned outages. One took the whole week off, one took the day off, one is on a week's leave for surgery etc. This shows that if planned well, some of the six operators working on ASY3 should have been assigned to ASY4 to ensure throughput from ASY4. But, the supervisor focused on output for just the 24th and not over a longer term. On 25th, operators were still processing ASY3, in spite of high WIP in ASY4.

Figure 7 highlights the variability in the operation throughput rates.

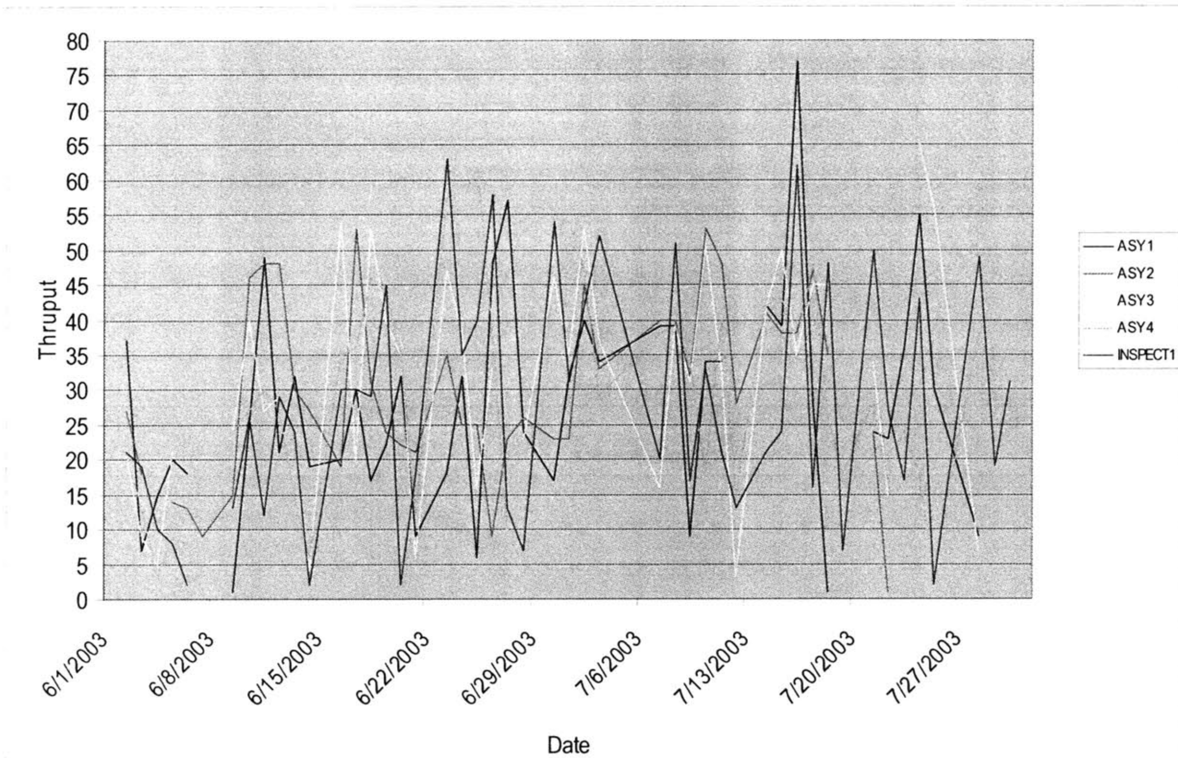

Figure 7: Daily throughput in June and July 2003 from the first five operations

4.2.6 Work Assignments

Most of the operators were assigned to specific operations and worked only on those operations. There were a few operators that were cross trained to work on multiple operations. There was a plan in place to cross train all the operators, but no specific deadline was assigned. The foremen believed that operators in general liked to work only on their assigned operations and did not like to get cross-trained.

4.2.7 Handling of Defective Parts

Parts that failed inspection were placed on the "Redrack" (Figure 6) that was used by all operations. A part could be placed on the Redrack by anyone at any operation. The manufacturing engineers were responsible for resolving problems and sending these parts back into assembly. The manufacturing engineer could access the part's status by entering the SFC number in SFDM. There were no limits on the number of parts on the Redrack. However, there was a general agreement with the customer that the parts on Redrack would be resolved by the manufacturing engineer and sent back to rework within two days.

4.2.8 Process Control

The Process Control group, different from Design and Manufacturing groups, proposed many initiatives for ensuring process control. Some of the initiatives included Statistical Process Control (SPC) of the Key Characteristics as identified by the Design Engineering group. At the start of the internship, the manufacturing group did not support these initiatives. The group was unwilling to collect the data required for ensuring process control and for data analysis by engineering. This was because the manufacturing group was busy dealing with production problems. Because the process was not streamlined (not under control), collecting data for this purpose represented additional non-value added effort and was not a priority at this stage. However, they were very supportive a few months later when the process was better streamlined, largely through demonstration that the information gleaned from this data was indeed value-added.

The ribbon bond process is a good example of Manufacturing's initiatives for process control. Manufacturing was very supportive of the new initiative (heated fixture) to improve the process. Their cooperation with the DOE[21] (Design of Experiments) helped the team identify ideal parameters to run the machine. The ribbon bond operation has since been using the SPC charts

[21] Balazs, Brett; *Visual Tools: Controlling and Improving the Ribbon Bond Process*, LFM Thesis, June 2004

and other process indicators, recommended by the other LFM intern[22], successfully to keep this process under control.

[22] Balazs, Brett; *Visual Tools: Controlling and Improving the Ribbon Bond Process*, LFM Thesis, June 2004

5 IMPLEMENTING CHANGE

The internship implemented process improvements and provided tools (addressing the three areas identified in the fishbone diagram, Figure 3) to resolve some of the problems that prevented effective execution of the production plan.

5.1 Culture

"*Employees are intelligent individuals who are motivated by work that keeps them informed about how their efforts affect the outcome and gives them power and responsibility to reach their goals.*" – The Visual Factory[23]

5.1.1 Key Performance Metrics

As mentioned in the earlier sections, this plant operated in a low volume culture. The assembly line was not equipped to measure and track the metrics in an effective manner. In addition, the metrics and frequency of measurement as identified by management were not in alignment with the performance goals. Consequently, the metrics and goals were not properly communicated to the people on the line.

The Cell Leader reported the progress twice a week to the plant manager. An example of this report is shown in Exhibit B. This report tracked the throughput of *every operation*, which meant that every operation was monitored. A production control support person spent four hours every day to gather all the data required to generate this report. While most of the data was available in SFDM, this data did not accurately represent the status on the floor (Section 5.3 explains

[23] Greif, Michael; *The Visual Factory: Building Participation Through Shared Information*, Productivity Press, Portland, Oregon, 1991

problems with SFDM). This necessitated frequent manual verifications to ensure the accuracy of the information reported to senior management. This was a much less efficient system than capturing the data accurately in the SFDM system once, and then using that information for analysis and reporting. This highlights a particular aspect of the prevailing culture - working around the problem rather than fixing the root cause of the problem.

The above report (Exhibit B) not only took a lot of time to generate but also failed to identify future actions. Therefore, the first step was to identify a set of Key Performance Metrics and provide tools to access the data for these metrics.

Implementation of Key Performance Metrics

To better measure the metrics, the internship established "Gates" at logical points at the end of certain operations. A "Gate" is a logical endpoint of a sequence of operations. The "Gates" were established based on the similarity and criticality of the operations. With the introduction of the "Gates", throughput was monitored at each individual "Gate", rather than at each individual operation. This simplified the line management because the throughput was monitored at fewer points (Gates). The Gate-based management also resulted in strengthening the *team* environment among the operators because they worked together to meet the throughput goals for their "Gate". An example of the report using "Gates" is presented in Exhibit C.

Apart from the daily throughput, the internship also identified a number of other key performance metrics (Exhibit D) based on benchmarking with other external and internal high volume manufacturing plants. The Raytheon Advance Product Center (APC) in Dallas especially provided useful information in this regard as they were also implementing Lean manufacturing in their facility.

The internship recommended that resources be allocated to ensure SFDM data integrity. This not only saved time but also ensured data integrity - expected and necessary for any data analysis. The tools provided by the internship made it possible to use SFDM data to generate the key performance metrics more efficiently.

5.1.2 Visual Control

The assembly area did not have any visual controls. The displayed range charts were not updated on a regular basis. The operators were unaware of how their contributions were affecting the overall objectives of the assembly line.

Importance of Visual Controls

Greif[24] compares the lack of visual controls in a factory floor with playing baseball where no one knows the score. A score makes it interesting by defining what it means to win and whether you have a chance of winning. It tells players how their individual efforts contribute to success.

In a single glance, visual controls make the information available and understandable for everyone in the factory, changing the culture of the workplace with "sharing" as the key principle. This also signals that the culture of sharing information, promotes the sharing of responsibilities and success.

Implementation of Visual Controls

The internship recommended displaying those parameters that convey a message both for internal and external groups. If a message is overly internal the group may not perceive a need for this kind of communication. On the other hand, if the message is geared for outsiders, the group will lose interest.

[24] Greif, Michael; *The Visual Factory: Building Participation Through Shared Information*, Productivity Press, Portland, Oregon, 1991

Success of visual communication depends not only on the message but also on the location. The internship established the location for placing the visual controls – this was the same location from where the Cell Leader often addressed senior management and external plant tour guests. The choice of the location was based on the concept of "Visual Territory". The visual territory is a place that promotes the group's cohesion and also is visible to the outsiders.

The visual controls identified above (Exhibit E) to improve communication proved to be so useful that Raytheon initiated efforts to display these on TV monitors directly from the shop floor control system.

5.1.3 Communication

The interviews with the operators identified that there was inadequate communication between the operators and management. The line did not hold daily production meetings. An example of lack of communication: when asked who updated the charts on the walls and what they implied, no one on the manufacturing floor except the Cell Leader knew the answer. Though there were charts on the walls showing throughput rates and goals, people on the floor were unaware of this.

Previous efforts by the supervisors to conduct daily meetings to communicate the status failed due to the fire-fighting nature of managing the line. The management also felt that the operators were not really interested in the status. However, informal conversations with the operators revealed that they *did* want to know how *they* were going to meet the required daily production rate, while catching up with the increasing backlog.

The Andover plant, as part of the initiative to improve employee involvement introduced the concept of "Raise Your Hand" (RYH) contact in each of the cells in the plant. Most of the employees in this cell were not aware of who their RYH contact was. When operators had issues, they directly communicated with their supervisors. The management was effectively resolving these issues, but the process or the progress was unclear. There was a general belief that management did not listen to the operators. So the operators did not take part in process improvements or provide any feedback. This was clearly a major shortcoming, since being the people actually touching and building parts, operators are the best people to get ideas from to improve the process.

Importance of Communication

In a low volume line, operators are like craftsmen who take ownership of their work. If there are process improvements to be made, they either implement these themselves or make sure they are taken care of. Therefore, the management may not have to explicitly solicit their feedback. However, in a high volume line this communication becomes critical not only to get ideas but also to get the operators' buy-in for any process improvements. Effective two-way communication is necessary for the successful implementation of processes that lead to line coordination. Improved communication would help in building employee morale and hence the productivity.

According to Job Characteristics Theory (JCT)[25], five job dimensions are critical to human performance. These are (1) skill variety, (2) task identity, (3) task significance, (4) autonomy, and (5) task feedback. This indicates that operators get motivated if they feel that they are working on important tasks (task significance), and they would like feedback on how they are doing (task feedback).

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[25] Genaidy Ash M. and Kawowski, Waldemar; *Human Performance in Lean Production Environment: Critical Assessment and Research Framework*

Improving the Communication

The internship introduced a daily10-minute meeting with a set agenda, to foster the communication between management and operators in the cell. The meeting was facilitated by the Cell Leader who addressed all the cell members, including the manufacturing engineers and the supervisors. This enabled the dissemination of the same information (goals, catch-up plans, issues etc.) to everyone at the same time. In addition, limiting this kind of communication to once a day at a scheduled time avoided the earlier problem of interrupting work for ad-hoc communications.

The internship also recommended that the meeting be held in a special area so the operators would get away from their workstations to attend the meeting. The location for the daily meeting was the visual territory identified to place the visual controls. This place in the cell is open and large enough to accommodate the whole group. Also this is the place the Cell Leader normally uses to address senior management and external plant tour guests.

As expected, there was a lot of opposition mainly because people perceived that operators were being taken away from their "work" for almost an hour every week. This kind of thinking reinforces the "Work harder" culture where working longer is more important than achieving the objective. It took considerable effort to make people understand that participating in these meetings is part of the "work" for the operators because they need to know the status and the catch up plan.

The internship also introduced an issues log, to log and track issues to make them visible to everyone. These meetings were also a vehicle to share these issues and their status. The issue log would be maintained by the "Raise Your Hand" contact in the cell.

After holding these meetings for about two months, the Cell Leader decided to hold them once a week instead of daily, with a group of four to five operators at a time. This was because the supervisors believed that the operators did not see any benefit in these meetings since the daily cell meetings did not address the operators on an individual basis.

These daily cell meetings did not provide the expected benefits for the following reasons (some of these are recommended for further analysis by subsequent internships and are not considered as part of this thesis):

- The line starved quite often due to a lack of material. The charts (visual controls) showed that the throughput was constantly lagging behind the goal. This resulted in people losing interest in the charts. This violates the first rule of the *three golden rules of displayed objectives*[26] that states *"The objective must be realistic. It must be attainable in terms of the available resources and organization's rules."* As material has been an ongoing problem and the management did not share how they were going to solve this problem, the workers did not perceive the goal as attainable.
- The agreed upon agenda included discussing the catch-up plan, if the previous day's throughput rates were lower than the required rate. This was never addressed in these meetings. This violates the second rule *"The objective must be precisely defined, with a predetermined level of accuracy."*
- The supervisors were expected to go over the daily work plan (Exhibit F) with each of the operators at the start of a shift and later in the day as needed. The intent of the daily meetings was to bring the whole group together to discuss the status at a high level to provide the same

[26] Greif, Michael; *The Visual Factory: Building Participation Through Shared Information*, Productivity Press, Portland, Oregon, 1991

information at the same time to everyone. The daily cell meetings were not intended for discussing the daily work plan because this could change during the day.

However, the supervisors never discussed the proposed daily work plan with the operators as proposed. Instead, the Cell Leader covered this in the daily meeting highlighting the operations that needed to be worked and those that didn't need to be worked on. Some of the operators might have been working on the operations that didn't have to be worked, making the operators feel like they had wasted their morning.

- The person responsible for updating the issue log did not update it often enough. This sent the message that this chart, that highlighted the workers' issues, was not important enough for management.

5.2 Manufacturing

"*Every product or service is the outcome of a process. Therefore, the effective way to improve quality is to improve the process used to build the product. The corollary of focusing on process is that the focus is not results – results are dependent variable. The results come from whatever process is followed, i.e. process drives results.*" – Four Practical Revolutions in Management[27]

[27] Shiba, Shoji and Walden, David; *Four Practical Revolutions in Management: Systems for Creating Unique Organizational Capability*, Productivity Press, Portland, Oregon, 2001

5.2.1 Production Plan Execution

The contract for the ongoing program was to make close to 3000 parts. However, the assembly line had a large amount of WIP, more than 2000 parts in July as shown in figure 8.

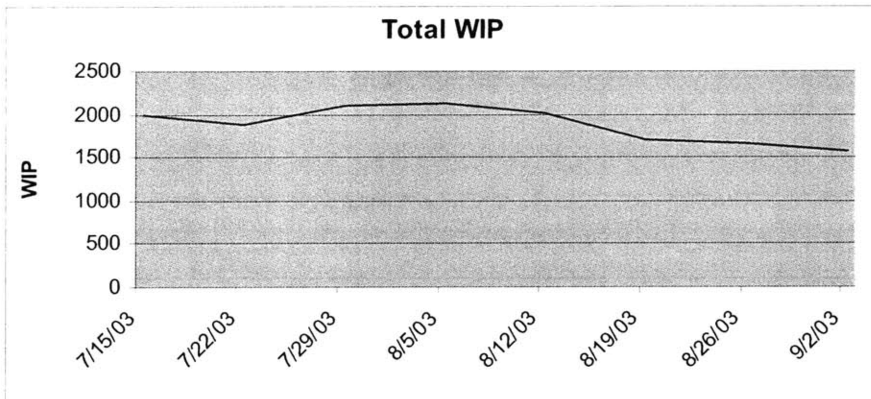

Figure 8: Total WIP Levels in July and August 2003

Having a large amount of WIP has the following effects:

- Adds confusion due to the clutter
- Requires additional resources to keep track of and to handle material on the floor
- Hides problems - Takes longer to resolve the problems because the identified problem may be due to the work done much earlier (a few days/week back) instead of work done recently (a few hours back)
- Takes up valuable floor space
- Increases variability
- Increases cycle time

Improving Production Plan Execution

The push system dictated by MRP and the lack of production run rules made it difficult to prioritize the work. The supervisors had no tools to dynamically execute the evolving production plan. Therefore, there was no consensus on executing the production plan. Balancing the flow is not possible in the absence of a common understanding of goals and priorities. The high amount of WIP and the lack of long term planning led to decisions that increased variability in the line.

Apart from providing run rules to prioritize the work, the internship recommended maintaining finite sizes for each of the input buffers to ensure line coordination. We determined the buffer sizes based on the following:

- throughput requirements of the line,
- complexity of each operation,
- bottleneck operations in the line, and
- the importance of an operation in providing feedback to its upstream operation

The assembly line required buffers between the operations mainly because of the various design, material and process problems. These buffers helped in decoupling downstream operations from upstream operations so that any interruption in the upstream operation had minimal or no impact on the downstream operations. This was one way to insure robust manufacturing, especially in a high volume manufacturing environment with rapid design and process improvements where interruptions are likely to occur often.

We developed a new tool called the "Daily Work Plan" (Exhibit F), to better execute the production plan. This tool visibly identifies the operations that needed to be worked, and the operations that did not need to be worked, based on the buffer sizes and the required daily throughput rate. Effective use of this tool would not only result in sustained line coordination but also lead to a self-directed workforce where the operators in a cell do not have to wait for the supervisors' direction for work assignments.

The line was also behind schedule due to the technical problems faced in the early months. This increased the daily required throughput rate to 75 per day from the initial 30 to 45 per day. The management brought in an expeditor to help pull material through the line. Expediting helped in pulling an extremely large amount of WIP through the line, but all the attention was focused primarily on the bottleneck known at that time (ribbon bond operation). Moreover, expediting increases variability, though it works as a short term solution.

We implemented a framework to determine the bottleneck in the line based on capacity and Takt time. This helped in determining that once the ribbon bond process was fixed, the test machine would be the bottleneck. It is important to identify and manage bottlenecks in the system because the throughput of the system is dictated by the bottleneck throughput.

Research conducted on the production plan execution of other high volume factories within Raytheon showed that using a pull system as advocated by Lean manufacturing would be the best solution to reduce the WIP and variability in throughput rates. In contrast to the push system, the pull system controls the WIP based on the actual throughput from the system, instead of the planned throughput. In other words, a pull system makes it possible to adjust the WIP based on actual capacity and other constraints on the resources without overproducing. The "Daily Work Plan" was developed to support the implementation of a pull system.

In addition, a pull system has the following advantages over a push system[28]:

- In a given system, it is easier to observe and control the input parameters than the output parameters. Hence, WIP (input to the assembly line) is *easier to observe and control* because the output depends on various factors like capacity, yield from each of the operations.
- The average WIP level required in a pull system is in general less than that required in the push system for the same throughput. According to Little's law, lead time is proportional to the WIP, making the pull system *more efficient* than the push system.
- Another important advantage of the pull system is *less variability* in throughput rates and cycle times. In a push system, the WIP levels at each of the operations are independent of each other, resulting in variable cycle times and hence variable lead times.
- Because the WIP levels are controlled in the pull system, the WIP levels at each of the operations can be tuned based on the importance and complexity of the operation (bottleneck vs. non-bottleneck). This makes the pull system *more robust* than the push system.

Instead of using Kanban cards, we recommended using the shelves in the racks for controlling the WIP for each operation. See Exhibit G for an example. This implementation satisfies the three basic requirements for visual production control[29]:

1. "The rule for initiating an order is visible" – We allowed the operators to work on an operation only when there was space in the output rack. The shelves in the rack were divided and clearly marked to accommodate the number of parts allowed to be placed in the output rack.

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[28] Hopp, Wallace J. and Spearman, Mark L.; *Factory Physics, Foundations of Manufacturing Management*, Irwin/McGraw-Hill, Boston, MA, 1996

[29] Greif, Michael; *The Visual Factory: Building Participation Through Shared Information*, Productivity Press, Portland, Oregon, 1991

2. "A high level of employee involvement exists" – The "Daily work plan" tool (Exhibit F) along with the empty spaces in the racks helped the operators decide which operation(s) needed to be worked on, instead of waiting for direction from their supervisor.
3. "A more visual system is difficult to imagine" – This rule suggests that the chosen system meets all the required objectives. Though using Kanbans for pull systems is industry practice, using the shelve space is better suited for this environment as it does not create extra work to manage Kanbans.

Effective implementation of the pull system provides a good example for the importance of changing the culture to Lean versus using Lean principles. A pull system does not allow for an operation to be worked on unless a downstream operation pulls material from this operation. The supervisors understood the value of the pull system, but did not want to stop production even if the buffer levels were at their maximum. They were concerned that if an operation was stopped to avoid overproduction, operators might be idle at that time. For a manager walking by, this might seem like excess capacity and provide motivation to reduce manpower. This concern highlights the fact that changing the culture is essential to reap the benefits from the application of Lean principles.

A pull system's success also requires availability of resources 100% of the time. This implies not only machine reliability but also cross-trained personnel. Literature on Lean, including *Lean Thinking*[30] recommend cross-training as one of the necessary steps to pull the product through a flow line. Though this line had plans to cross-train people, practical aspects did not make it possible to achieve 100% cross-training. This line requires highly skilled labor, but the unionized workforce makes it difficult to choose the optimum mix of skills in a continually dynamic

[30] Womack, James P. and Jones, Daniel T.; *Lean Thinking*, Simon & Schuster, New York, 1996

manner. Therefore, the management preferred to assign the best workers to the more complicated operations, leaving others to work on the not so critical operations. This practice was not aligned with the cross-training recommendation, leaving the line in jeopardy when there was a shortage of people.

Interestingly, this project is unable to assess if the pull system helped in achieving line coordination, mainly because the line suffered from lack of material. Two of the suppliers, both internal, failed in delivering the material per schedule[31]. Without a continuous flow of input material to the line it is not possible to pull parts through the process, to satisfy the daily throughput requirements.

5.2.2 Floor layout

The cell scored very low in Lean Manufacturing's 5S/Workplace Organization. One of the areas that clearly needed improvement was the "Visual Factory". The racks and shelves in the area were not clearly labeled. There was a lot of confusion about the input/output racks for the operations. There were no production run rules displayed in the area.

Big cabinets containing finished parts obstructed the operators from seeing other workbenches. The layout also made it difficult for easy visual assessment of the WIP on the floor. There was a general belief among the managers that making the operators get up from their seats is highly unproductive not only for the wasted time spent in walking but also because of the time they would spend socializing with others. But the layout of the floor required the operators to walk a lot to take parts in and out of the racks.

[31] E-mail from the Cell Leader

The Raytheon Six Sigma^{TM} project to improve the floor layout provided a good opportunity to completely change the existing layout. We designed the new layout based on Lean principles. This U-shaped layout accommodates racks next to the workstations so the operators can access the required racks while sitting at their workstations. Because of the initiative to reduce WIP (moving from infinite size to finite size buffers), the number of racks needed was considerably reduced. This resulted in a compressed layout with less confusion and better visual management. Figure 9 shows the new U-shaped layout.

We determined the number of work benches for each operation based on the Takt time and the daily throughput requirements. The rectangles marked as "WB" in the figure below are the work benches and the rectangles marked as "R" are the racks for input buffers for each of the operations. In the previous layout the racks were in between the work benches. The new layout has work stations next to each other, with the racks placed in a separate row, within easy reach of the operators. Though there may be multiple work benches for an operation, there is only one rack (with the input buffer) for that operation. This makes it easy for the visual control of the WIP, so the operators can stop working when the buffer reaches its limit.

For example, the operators on work benches for ASY1, take the parts from the rack labeled ASY1 and place the processed parts in the rack labeled ASY3 (the next operation in the assembly process). The input racks for CLEAN operations are placed on the outer side of the work area because the machines for these operations are in a separate location in the plant. These racks are rollaway carts that the operators can move in and out of this work cell.

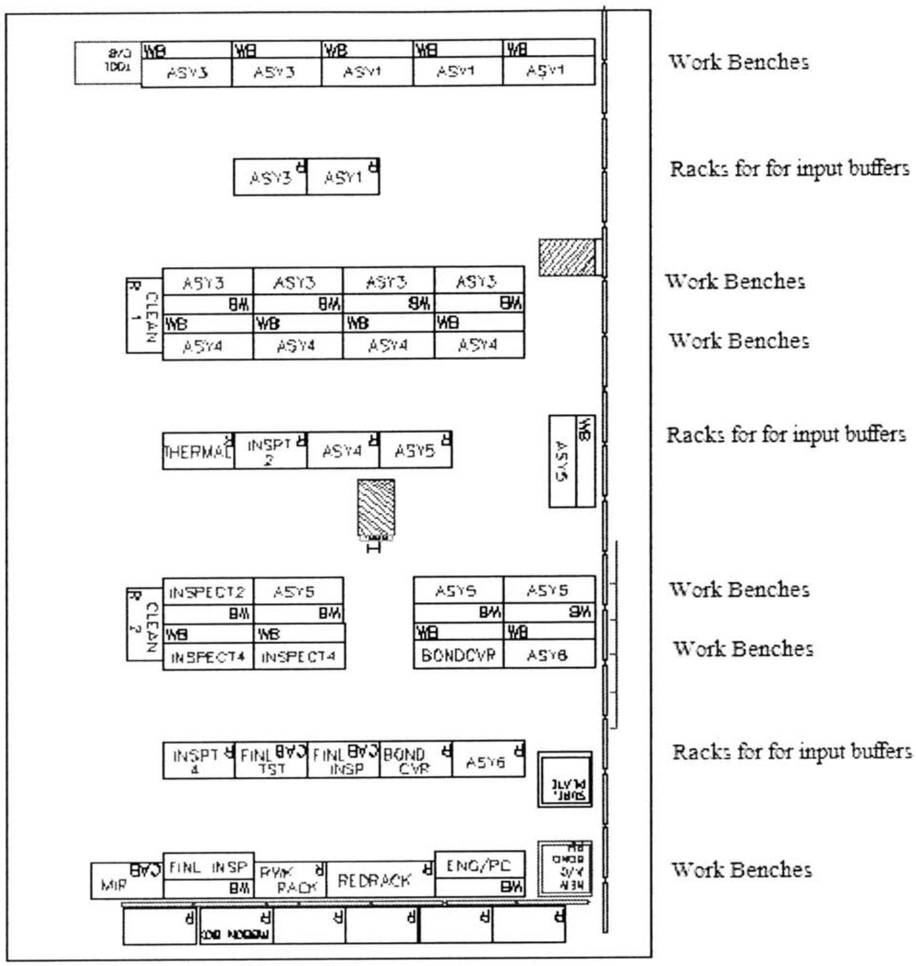


Figure 9: U-Shaped Floor Layout

5.3 Business systems

"*Information managers must begin by thinking about how people use information, not how people use machines*" – Saving IT's Soul - Thomas H. Davenport[32]

The Shop Floor Data Management (SFDM) system is a commercial off-the-shelf product for shop floor control. This tool requires extensive customization to cater to the specific business needs of the company/location of implementation.

[32] Davenport, Thomas H.; "*Harvard Business Review on The Business Value of IT*", A Harvard Business Review Paperback, 1993-1999

At Raytheon, the SFDM data was exported to a Microsoft Access database called Data Warehouse, to facilitate user defined queries and reports. The plant was in the process of rolling out this system in all the value streams. The IT group was responsible for this rollout and system level customization. The Process Engineering group created and maintained the line specific processes and work instructions (process sheet) in SFDM.

The sequence of operations in the assembly process was defined in SFDM along with each operation's standard time and work instructions. This sequence of operations was called a Router. The system tracked the operational and financial metrics in building the part based on the part's router. The manufacturing engineer defined the router and evolving work instructions based on formally issued Change Notifications. The process engineering group was responsible for creating and maintaining the router in SFDM.

When an operator, assigned to a particular operation, logged into SFDM, the system displayed all the parts (SFC numbers) to be processed in that operation. When the operator performed the operation on the part(s), he/she selected the SFC number(s) in the system and marked the operation as complete. These parts then proceeded to the next operation in the router.

The decision to purchase SFDM was made by the Raytheon division in Dallas, TX. They introduced this product to Andover. Though the IT group in Andover was trained to implement SFDM, most of the SFDM expertise resides in Dallas. Both SFDM and Data warehouse are managed and maintained by the IT group in Dallas. Because Andover did not make the decision to buy SFDM, a certain amount of a "Not Invented Here" feeling was prevalent among the users.

SFDM was introduced to this assembly line when the line was built. All the shop floor personnel attended the basic SFDM training. However, the operators did not undergo job/product specific training. The assembly area had no rules or standards for data entry. Because of this, the data was not entered in a consistent manner. A lot of time was spent on collecting data, but not in a form that was easy to analyze. Another problem was a lack of SFDM understanding. Because the users were not trained to perform their jobs, they had different interpretations of the same SFDM reports (even basic ones like Production report that is used everyday for making decisions).

Serious data integrity issues arose because of the following practice:

- When there was a change in the router, the operation names were also changed, even if the work done in the operation did not change. This was because process engineering wanted to have the operation names in sequence (e.g.: ASY1, ASY2, ASY3 instead of ASY1, ASY3).
- However, when the work done in a particular operation changed, the operations were not renamed.

The following example illustrates both these problems. The work done in ASY2 was split for some of it to be done in ASY1 and rest of it to be done later in the process. Though the work done in ASY1 increased (because of the part that was included from ASY2), the name of the operation was not changed. If one looked at the time taken for ASY1 over a period of time, the plot would show the time increasing but does not show the reason unless a considerable amount of time is spent to find out the date when exactly the operation has changed. This split also resulted in scrapping the ASY2 operation. Because the rule dictated that the operations had to be in sequence, all the operations after ASY2 were renamed, so ASY3 became ASY2, ASY4 became ASY3 and so on. If one wanted to analyze, for e.g. ASY4, historic *data* would give the wrong *information* because work done in the past in ASY4 was completely different from what was currently being done.

The low volume culture was evident in the implementation of SFDM as well. This kind of implementation practice was particularly challenging for this line not only because of the high volumes involved, but also because of the frequency of changes to the router. Data integrity issues may not be as critical in a low volume environment as they are in a high volume environment because the data can be easily verified by visual inspection. During the internship period, the router was revised almost every month. *In summary, the implementation did not allow for analysis or decision-making based on historic data. Also, if manufacturing introduced any process improvements, it was not possible to compare metrics like yield or time taken with historic data.*

The lack of a complete understanding of SFDM resulted in wrong expectations. At one point, while evaluating the cleaning operation for ribbon bond process, some parts went through an aqua wash and the others went through plasma cleaning. But there was only one CLEAN operation in SFDM to log both of these operations. Unfortunately, manufacturing expected SFDM to keep track of these separately and in the end there was no way to track which parts went through which of these operations. Because of this, one of the team member's hand-written notes identifying the performed operations became the basis for making one of the most important process decisions.

There was no accountability for the router implementation. Though manufacturing engineers design the router on paper, they did not approve the SFDM router before process engineering released it to production. Sometimes the released routers had errors. This can be attributed to two reasons:

1. When the process engineering group received a request to create or revise a router, the work was assigned to any available process engineer. There were no specific process engineers assigned to the value streams. This was because the management believed that common procedures had to be used across the factory, so they didn't have to allocate people based on the value stream. So, no one in the group understood the specific requirements for a given value stream.

   This practice worked well when all the value streams produced similar types/volumes of products. However, because this particular assembly line was different from the other ones due to its high volume nature, the common procedures did not address the specific needs for this line.

2. Once the router was created, manufacturing engineers did not see it till it was in production - the people who know and use the router did not get to approve it. The manufacturing people recognized this and wanted to be a part of the approval process but they were not willing to take the initiative to change the existing process.

Once a router was in production it was impossible to correct it because parts would have been built per this router. Unfortunately no one seemed to realize the effects of this because they were not using the data for any analysis.

The contract with the customer required Raytheon to deliver specified quality charts periodically. The Statistical Quality Control group created these charts. This group was located in a different part of the building and was unaware of these data integrity problems with SFDM.

All these problems became visible because the internship introduced and provided tools for electronic gathering of metrics. This resulted in hiring a SFDM expert for two months to address most of the data integrity issues.

The internship recommended special guidelines to the Process Engineering group, to address the needs of the microwave value stream. Following these guidelines would preserve historic data to facilitate data analysis for high volume manufacturing. The management agreed to use these guidelines and they incorporated these into the process development's SFDM guidelines that all their process engineers refer to.

6 CHALLENGES

The manufacturing area operated in a fire-fighting mode. The culture encouraged people to "work harder" instead of "work smarter". Because the people were busy with fire-fighting, they did not have the time to implement long term improvements.

Overcoming the conventional mindset - pushing product thorough the line and building as much as possible to fully utilize the manpower - was the biggest challenge during the internship. It took a considerable amount of time and many conversations with the manufacturing personnel to make them understand that "pulling" rather than "pushing" the product through the line was better for the long term. Though they understood this on a theoretical level, it was never the "right" time to start the pull system, because of the fire-fighting mode and the pressure to show immediate results. The new layout provided the impetus to switch to the pull system.

The other challenge to implement the necessary changes was the status-quo attitude of the people. In the LFM thesis[33], *The Soft Side of the Toyota Production System is the Hard Side*, Johnson describes this type of culture as a culture of "Reliance on the problem solver". He distinguishes between workers and problem solvers. He contends that in this culture, problem solvers due to special characteristics like charisma, status and authority have a distinct advantage to overcome the barriers to solve problems.

The research identified two types of people. The first type of people are those who do not challenge the status-quo because they are not aware that there is a better way of doing things.

[33] Johnson, Brent M.; *The Soft Side of the Toyota Production System is the Hard Side*, LFM Thesis, June 1998

They accept the situation they are in and work hard in their daily jobs. The example of the PC support person spending four hours per day counting parts on the floor is a good example of working hard instead of ensuring data integrity so they can get the data from the SFDM system. The other type are those who do not challenge the status-quo even though they know better ways to improve the current state. But these people do not feel empowered to take the necessary steps to make the change. This is because either they think that it is not their problem or they perceive the process to be too bureaucratic. This is illustrated by the example of manufacturing not taking any steps to approve the SFDM router before it was released to production.

7 CONCLUSIONS

The internship succeeded in making the management aware of the differences between managing a high volume line versus a low volume line. Benchmarking within Raytheon helped in introducing some of the best practices to this line. The new processes implemented by the internship are being adopted by other assembly lines in the cell as well.

Figure 10 shows the throughput by operation in June 2003. The throughput from the initial operations was significantly more than the throughput from the last few operations. The technical issues with the ribbon bond operation resulted in this, causing high levels of WIP before the ribbon bond operation. This kind of line management led to reworking of 700 parts after the technical issues were resolved.

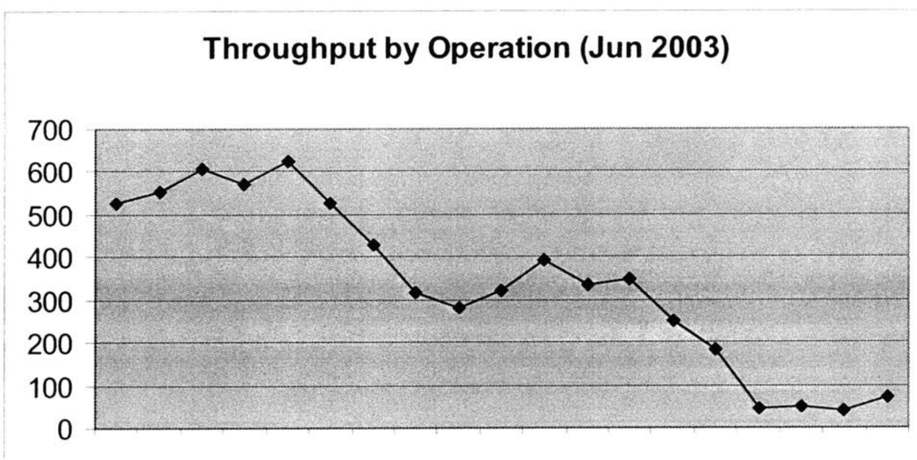


Figure 10: Throughput by Operation (Jun 2003)

In contrast, Figure 11 shows that the front of the line is more coordinated. The end of the line had high throughput because these operations processed the backlog from previous months.

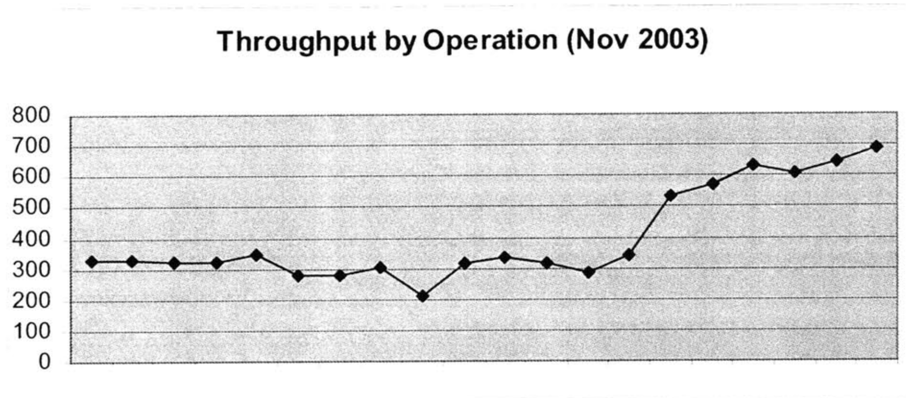


Figure 11: Throughput by Operation (Nov 2003)

The success of the efforts to improve communication using visual controls is evident from Raytheon's initiative to display these on TV monitors.

The tools provided to improve the production plan execution, like the "Daily Work Plan" are also being widely used and have led to better line coordination (Figure 11). The Gate-based line management is being used by other programs as well. The internship did not have the opportunity to evaluate the pull system implementation due to material shortages.

The program met its schedule and delivered the product on budget, despite the areas of improvement addressed in this thesis. But this was achieved with a lot of fire-fighting and unplanned overtime to accommodate the increasing target rates.

8 FUTURE WORK

8.1 CN Implementation in Manufacturing

Due to the number of technical problems during manufacturing, Engineering had to introduce frequent changes. They recognized the fact that these Change Notifications (CN) have to be processed faster than the CNs for other programs. So, they created a new change approval process called "Rapid CN approval" to approve critical CNs in this program. However, once engineering approved a CN, it fell in the same queue with CNs for all the other programs, sometimes taking up to two weeks for manufacturing to receive the CN. This resulted in Manufacturing having little or no time to prepare or plan, for the required changes.

The research mapped the current state of this CN implementation process in Manufacturing after Engineering approval. The project identified key stakeholders and brought them together to improve this process to reduce the two week cycle time. This effort is now covered by Raytheon's Radar Affordability project.

8.2 Calculating Sigma by Operation

The internship also started a Raytheon Six Sigma™ initiative to calculate sigma by operation. Calculating sigma by operation will help in identifying operations that need improvement. This will also help in calculating yields by operation to achieve continually improved line coordination. This initiative was handed over to the Cell Leader.

8.3 Surface Radar Procurement Strategy

During the term of the internship, there were many instances when the manufacturing line starved due to lack of material either from internal or external suppliers. Line coordination and Lean manufacturing cannot be achieved with these frequent, unplanned events. The internship also suggested that Raytheon sponsor an LFM internship to streamline their procurement strategy. With its commitment to Lean manufacturing, Andover site is sponsoring this internship[34] in 2004.

8.4 Transforming Data to Information

The present LFM internships identified and escalated the problem with capturing too much shop floor level data that is not useful. One example of this problem is the non-conformance (defect) data that is entered into SFDM. The data collected makes analysis on types or frequency of a certain type of defect practically impossible. The operators spend more time entering this defect data than they actually spend inspecting the part. These internships highlighted the importance of collecting information versus data.

This effort is also a candidate project area for LFM interns in 2004[35].

[34] https://lfmsdm.mit.edu
[35] https://lfmsdm.mit.edu

Exhibit A

Raytheon 6S Checklist

ENTER 5, 3, or 1 to the yellow SCORE area

Rank 5 points; No problems found
Rank 3 points: 1 - 2 problems found
Rank 1: 3 or more problems observed

Category	Item	A	B	C	Comments	Score
SAFETY	Machinery - Are safety guards and switches in place and visible?	5	3	1		
Total 15 points	Aisles - Are aisles clear and emergency exits signs in place?	5	3	1		
Reference document	Electrical - Are there potential electrical hazards (damaged cables, cables on floor, emergency shut-off's not available,etc.)?	5	3	1		
	Alarms - Are all safety alarms and indicators working and visible?	5	3	1		
	Visual Aids/Warning Labels - Are labels and warnings legible?	5	3	1		
	Environmental Hazards - Are chemicals properly stored?	5	3	1		
	Fire - Does area have fire emergency plans and received training?	5	3	1		
	Personal - Are area requirements established and being used?	5	3	1		
SORT/Sift	Have all unnecessary Bench and POU items been identified?	5	3	1		
Total 20 points	Have unnecessary Bench and POU items been tagged?	5	3	1		
	Have unnecessary Bench and POU items been dispositioned (per a removal process)?	5	3	1		
	Have unnecessary items been removed (in a timely manner)?	5	3	1		
STORE/Sort	Bench Area - Are materials, tools, fixtures, documentation properly identified/labeled?	5	3	1		
Total 20 points	Bench Area - Are materials, tools, fixtures, documentation put-away correctly after use?	5	3	1		
	P.O.U. - Are materials, tools, fixtures, documentation properly identified/labeled?	5	3	1		
	P.O.U - Are materials, tools, fixtures, documentation put-away correctly after use?	5	3	1		
	Bench/P.O.U - Are all stations clearly identified with signs?	5	3	1		
SHINE/Sweep	Are Bench, P.O.U. & packaging material kept clean?	5	3	1		
Total 15 points	Is equipment (test stations, ovens, etc.) kept clean?	5	3	1		
	Are cleaning materials properly identified and easily accessible?	5	3	1		
	Are cleaning guidelines and schedules easily visible?	5	3	1		

	Are demarcation lines clean and unbroken?	5	3	1
	Is equipment, benches, and general area painted/refurbished to look as new?	5	3	1
	Are waste bins overflowing?	5	3	1
STANDARDIZE/	Is there a radar chart, 6s checklist in the area?	5	3	1
Sustain	Is there a run rule for identifying/removing unnecessary items?	5	3	1
Total 20 points	Is there a run rule for cleaning the bench and P.O.U.?	5	3	1
	Is there a 6s schedule?	5	3	1
	Are there identification run rules for bins, racks, signs, etc.	5	3	1
	Are there "put-away" run rules for chemicals, calibrated tools, standard tools?	5	3	1
	Are ergonomic run rules being followed?	5	3	1
	Is there a 6S champion and run rules for inputs to the champion?	5	3	1
	Is the 6s achievement/celebration criteria known?	5	3	1
SUCCESS/				
Self Discipline	Are previous actions closed in a timely manner? If not, has it been escalated to upper management? Are before / after photos visible?	5	3	1
Total 10 points	Is the radar chart improving?	5	3	1
	Does area manager regularly encourage and explain 6s for the area?	5	3	1
	Is success openly celebrated and the events recorded?	5	3	1
	Does area manager give rewards for participation in 6S?	5	3	1

Exhibit B

Weekly Progress Report (June 2003)

CUM

W/E	5/30	6/6	6/13	6/20	6/27
AIMS	1701	1901	2101	2301	2501
O	1337	1562	1787	2012	2237
A	618 equiv	707 equiv			
DTM	-1308				
Recovery	393	618	843	1068	1293

Current Rate Goal of 45

CUM

Month	APR	MAY	JUN	JUL	AUG	SEP
AIMS	901	1701	2501	3222	3222	3222
O	462	1337	2237	2962	3222	3222
A	0	0				
DTM	-901	-1701				
Recovery	0	618 equiv	1293	2148	3168	3222
Req'd Daily Rate			45	45	50	

Current Week Cum Outlook Equivalent Units: 800

Mdays to MIR		7		6	3	2		1			0	
OPER	ASY6	RINSPECT2	ASY7	TST1	TST2	TST3	TST4	INSPECT3	ASY8	FINALTST	FINISP	COMPLETE
AVAL	44	7	22	129	57	83	39	128	8	80	188	46
CUM	831	787	780	758	629	572	489	450	322	314	234	46
Rework Insert	1	2	8	42	0	19	0	1	0	16	4	

ENGINEER REVIEW RACK	5
RED RACK	4
CCA RWK	2
WTG MATERIAL	24
WTG REWORK	105
	140

Mdays to MIR			12		11		10			9			8
	C/B	OPER	KIT	ASY1	ASY2	ASY3	ASY4	INSPECT1	CLEAN	RBNBOND1	ASY5	INSPECT2	RBOND
13553509-1 TRIMM		AVAL		152	10	54	70	40	162	180	35	36	79
		CUM	1727	1727	1497	1487	1433	1363	1323	1161	981	946	910
Rework Insert				1	0	3	8	8	1	5	0	6	12

Exhibit C

Report Based on Gates

3100	Total Hrs	ASY1	ASY3	ASY4	INSPECT1	Clean1	ASY5	Clean2	RBNBOND1	RIBPULL	INSPECT2	ASY5	ASY6	TST1	TST2	TST3	INSPECT4	ASY7	FINALTST	FININSP	COMPLETE
MFG METRICS		GATE 1				GATE 2				GATE 3				GATE 4		GATE 5				GATE 6	
Average Daily Completes Since 8/7:																					
STANDARDS	5.4	0.4	0.1	0.7	0.1	0.2	0.1	0.3	0.5	0.3	0.4	0.7	0.5	0.1	0.2	0.2	0.2	0.2	0.2	0.1	
EST OPER K-F		2	3	2	2	1	2	2	2	2	2	3	2	1	1	1	2	2	1	2	
EST FACTOR HR	9.5	0.7	0.3	1.3	0.2	0.1	0.3	0.6	1.0	0.3	0.5	1.6	0.9	0.1	0.2	0.2	0.4	0.3	0.2	0.2	
GATE HRS	9.5	2.6				2.0				3.3				0.3		1.1				0.2	
CUM COMPLETE		2530				2366				2042				1366		1398				1146	
BAL RADAR 1		570				734				1058				1734		1702				1954	
EST. COMP_DATE		2-Sep				9-Sep				16-Sep				22-Sep		26-Sep				30-Sep	

Exhibit D

Key Performance Metrics

Apart from the metrics identified for visual controls, the internship identified the following metrics to monitor.

WIP

- Aging WIP > 30 days gets flagged
- Out of flow WIP - what % of total WIP is in rework?
- WIP as a total

Cycle time

- Daily Dynamic cycle time (WIP/shipped for a day)
- Total cycle time (days in the factory)
- Value added cycle time (theoretical cycle time)

Labor

- Overtime
- Labor Productivity - Units Produced divided by labor hours (all hours worked, including overtime).

Quality

- First pass yield
- DPU = Total number of defects identified on all units/ number of units
- Operation DPMO (Sigma by operation)

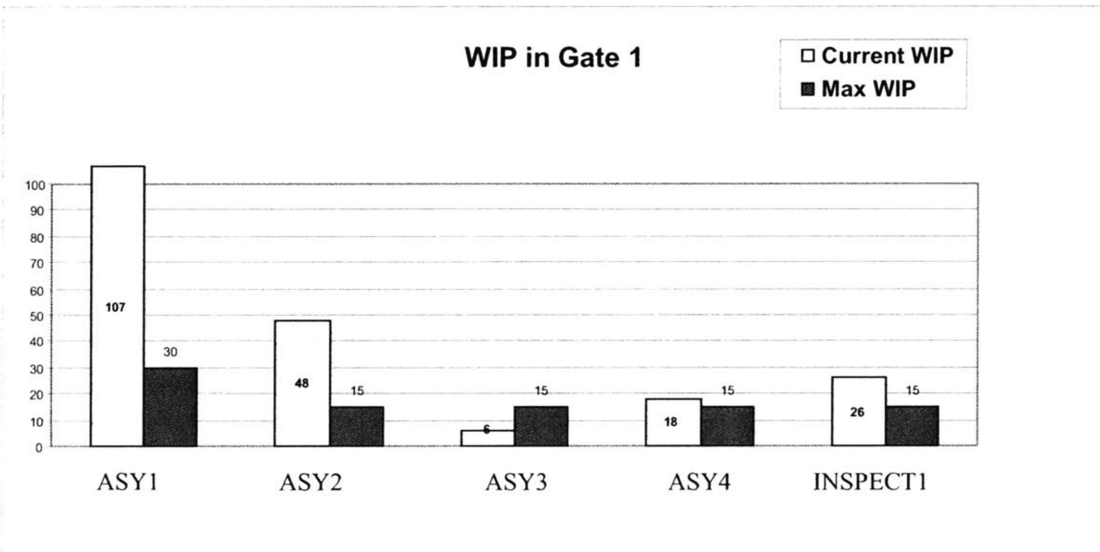
Exhibit E

Visual Controls

This exhibit shows a few of the visual controls identified by the internship. Production meeting agenda, Production meeting run rules, the Issues log and Production run rules are some of the other visual controls not shown here.

WIP Charts

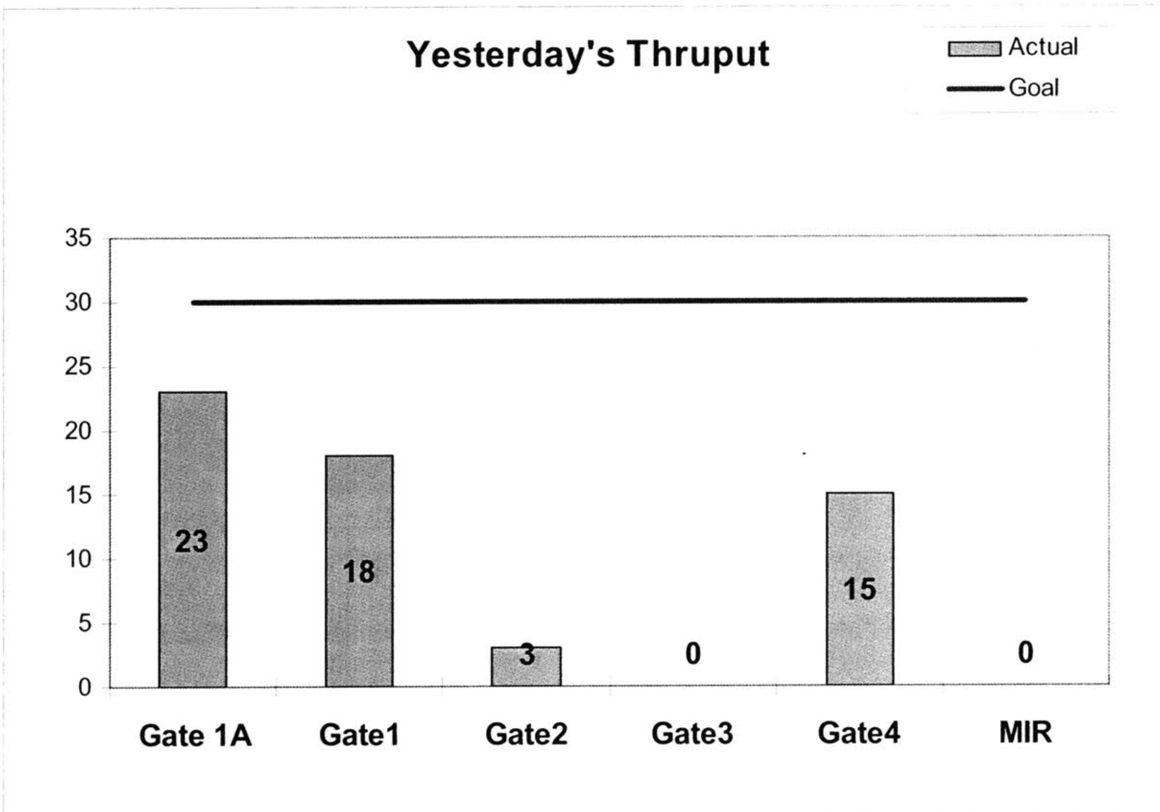
The WIP charts display the current WIP for each of the identified "Gates". The example in the following chart shows the WIP in Gate1. Operators are allowed to work only on operations that have a current WIP less than the Maximum WIP (buffer limit).



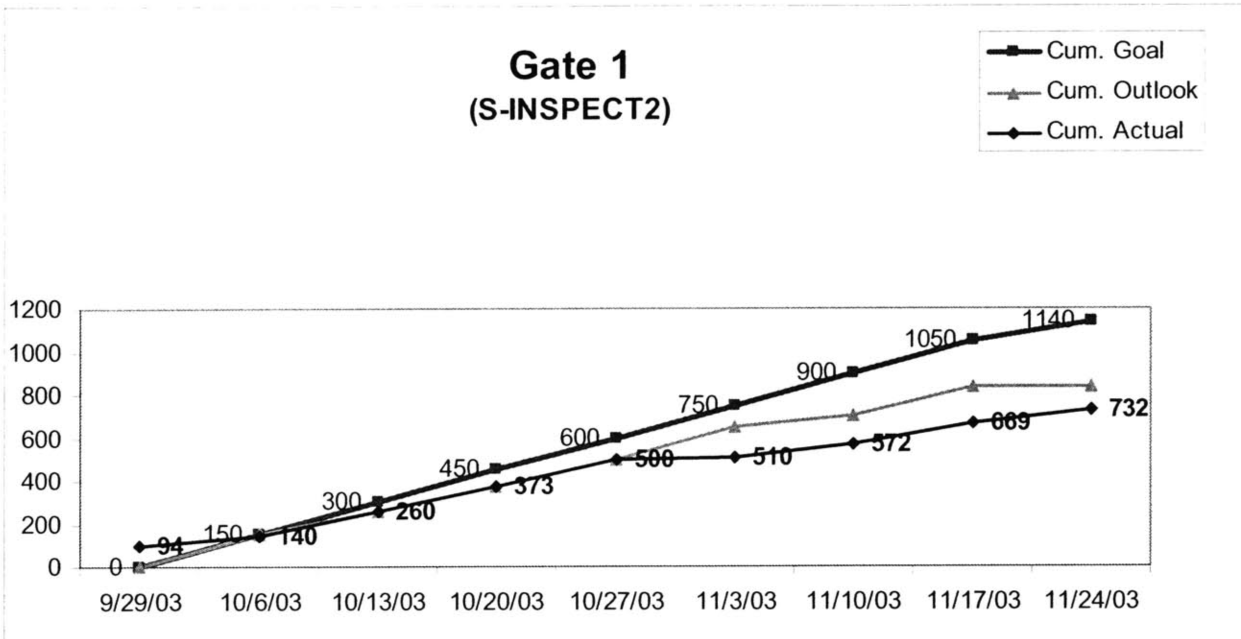
Current and Max WIP levels for each of the operations in Gate1

Throughput Charts

There are two types of Throughput charts – (1) Yesterday's throughput and (2) Weekly cumulative throughput, at each of the "Gates". The throughput at a "Gate" is the throughput from the last operation in that "Gate".



Previous day's throughput against the goal for each of the Gates



Weekly Cumulative Goal, Outlook and Actual Throughput for Gate1

Exhibit F

Daily Work Plan

	11/20/2003					
Operation	Max WIP	Current WIP	Gap	Today's Req	Req Rate	# Ops
ASY1	30	215	(185)	72	60	7
ASY2	30	18	12	65	60	3
ASY3	40	35	5	69	60	12
INSPECT1	20	11	9	112	60	3
ASY4	80	28	52	127	60	1
ASY5	80	13	67	42	60	1
INSPECT2	20	38	(18)	76	60	2
ASY6	27	11	16	15	60	1
ASY7	27	72	(45)	(32)	60	0
ASY8	6	98	(92)	(97)	60	0
INSPECT3	66	223	(157)	53	60	4
ASY9	20	27	(7)	(10)	60	0
TEST1	80	150	(70)	92	60	1
TEST2	80	63	17	99	75	1
TEST3	60	21	39	74	60	1
ASY10	30	35	(5)	74	60	13
INSPECT4	20	6	14	69	60	4
ASY11	20	11	9	27	60	1
TEST4	20	56	(36)	61	63	1
INSPECT5	20	19	1	38	60	1
COMPLETE	20	42	(22)	60	60	1

Start working right away (Need > half daily req)

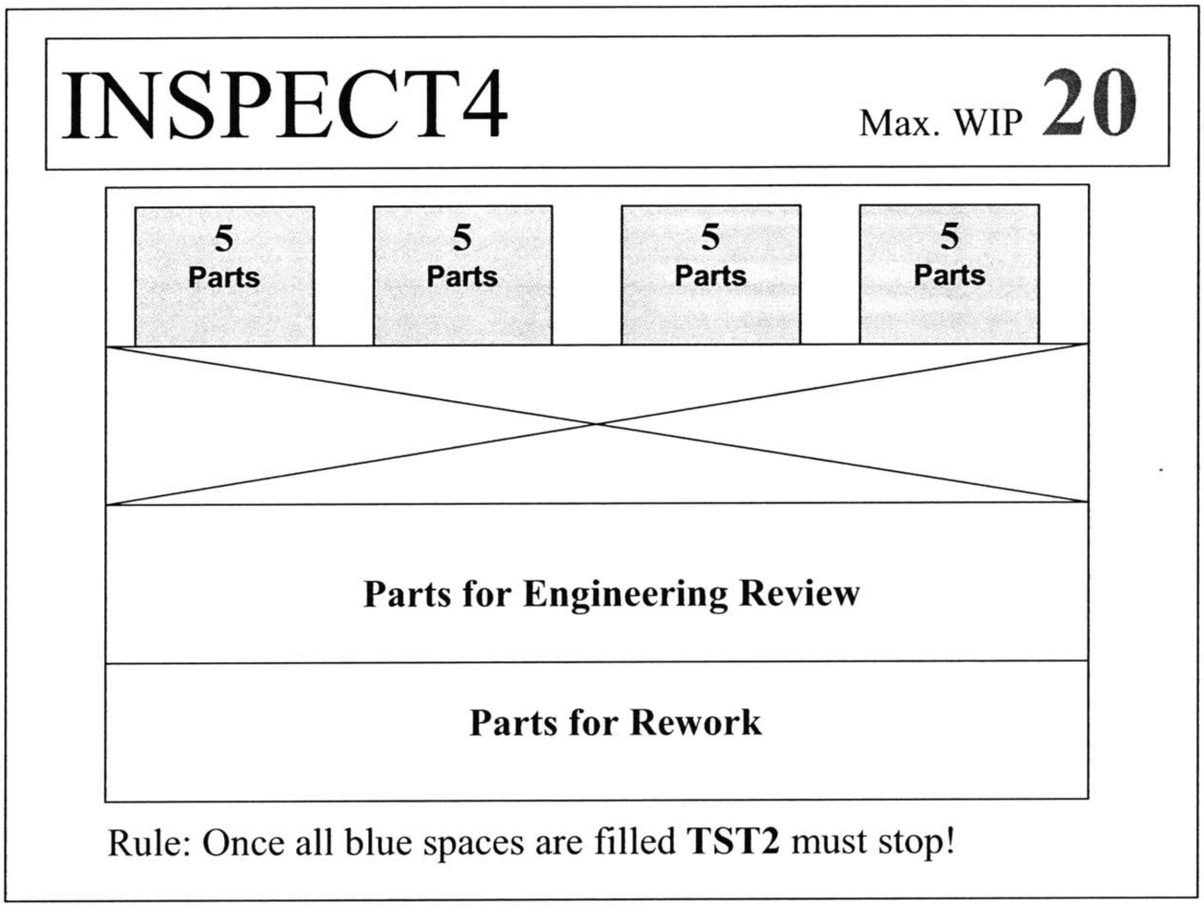
Can wait to work on these (Need < half daily req)

Don't work

Exhibit G

Sign on the Racks

The following figure is an example of the signs for the racks carrying input buffers.



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