A Lean Transformation in Low Volume Space Manufacturing

by
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Bachelor of Arts in Physics, Bowdoin College, 1997

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

Master of Science in Ocean Systems Management
and
Master of Business Administration

In Conjunction with the Leaders for Manufacturing Program at the
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ABSTRACT

Lean manufacturing has its roots in the automotive industry. Toyota Motors developed much of the methodology after World War II, where scarce resources and low capital forced an alternative to the traditional high volume, batch-flow, automotive manufacturing. Toyota competed with the larger American firms on both quality and price, using a system that required less capital investment. Today, Toyota Production System (TPS) practices have been incorporated into the production systems of many large manufacturing firms. While these firms have seen much success, lower volume manufacturers have been slower to embrace these practices. This has been true for the aerospace industry – particularly for those firms that manufacture space products. Much of the manufacturing for space products is still done in job shops to accommodate for the low volume and high degree of complexity associated with their products.

This thesis explores a case study of transitioning to a lean manufacturing system, in a low volume space manufacturing environment. Much of the work in this thesis reflects a seven-month internship at Raytheon Corporation's Space and Airborne Systems group, through a partnership with the *Leader's For Manufacturing* program. This thesis will analyze both the difficulties in transforming a low-volume shop of this type, and the potential rewards of higher productivity and quality.

Perhaps the most difficult transition in a lean transformation is a change in corporate culture. Traditional space manufacturing is quite structured, in that detailed planning is determined by people outside of assembly. This thesis will also look at the organizational difficulty in shifting decision-making power supervisors to assemblers.

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I would like to thank Raytheon for hosting me a full seven months, and allowing me to implement changes within their facility. In particular, my project supervisor Kirk Winn provided invaluable feedback and support - the project would not have been possible without his help, and I will continue to look for his advice in my coming years at Raytheon. I would like to thank my project champion Ken Brown, for his help in motivating proposed changes throughout the internship. And finally, I need to thank Don Freudenthal, who fully supported the changes we made to his lab.

Thank you Professor Eppinger and Nightingale – your guidance gave much momentum to this project, both in narrowing an initial area of interest and in providing feedback during later company visits.

Finally, I would like to thank my family for their continued love and support.

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1.0 Introduction

1.1 Background of Raytheon

Raytheon was founded in 1922 in Cambridge, MA as the American Appliance Company. Former college roommates Laurence K. Marshall and Vannevar Bush (MIT Professor of Electrical Engineering) joined young engineer Charles G. Smith to sell refrigerators. Charles had developed a prototype refrigerator that could cool using artificial refrigerant. This venture failed and in 1925, the company was renamed "Raytheon."

Throughout its 75-year history, Raytheon has laid claim to numerous innovative products. Perhaps one of the most widely recognized is the commercial microwave. Percy L. Spencer – an engineer with only a grade school education, invented this. Percy first convinced British scientists they could develop and produce a microwave transmitting tube, integral to the radar system designed to detect invading German aircraft. While working on this project, Spencer noticed a chocolate bar in his pocket melted while working near a microwave tube. Curious, he placed corn kernels in front of the microwave, which then popped. On his third experiment, he placed a raw egg in front of the tube and unexpectedly became the first person to explode an egg in a microwave! Perhaps some of the other widely recognized Raytheon innovations are magnetron tubes, shipboard radar systems, guided missile systems, NASA communication systems, and the Patriot missile system.

The El Segundo facility was an acquisition, originally a part of Hughes Electronics. At one time, the facility was owned by a hospital and operated under not-for-profit status. Its forced sale to General Motors marked a transition to for-profit, a status that continued through a subsequent sale to Raytheon.

Today, the facility is named Space and Airborne Systems (SAS) and builds diverse products supporting programs ranging in launch height from TOW missiles to Global Hawk to satellites. Each of these programs is based on fairly low production, and customized engineering. This is particularly true for the satellite builds, where total production is usually fewer than five units per year. Throughout the company's history, there have been shifts towards manufacturing more components in-house and shifts to outsource production. Today, there is little – if any – "manufacturing" done at this facility. Some of this is because of higher costs associated with manufacturing on the beaches of Southern California - some of this is also grounded in a belief that it is not possible to manufacture space products, because they are so diverse in nature. In fact, one of the Directors of Engineering simply stated "we do not do manufacturing here." While it is probably more accurate to state "we do not do *traditional* manufacturing here" - Raytheon does produce components that are similar in nature. However, they are produced in low enough volumes, with a high enough degree of product mix, that a traditional assembly line would not be efficient.

1.2 Background of LFM Program & LAI

In the early 1990's, the benefits of lean manufacturing spread throughout the USA, as there was a large gap in both the efficiency and quality between American manufacturing firms and their foreign counterparts. This was particularly true for American automobile firms, which were losing much ground to cheaper and better built Japanese cars. The popularity of lean manufacturing spread fast after the publication of the book "The Machine That Changed the World." In the late 1980's, the LFM program was established as a partnership between MIT academia and partners in industry. Graduates from this program would be trained in the elements of lean manufacturing, bringing these skills back to industry. Separate from LFM, the Lean Aerospace Initiative (LAI) was established to specifically bring these lean philosophies to aerospace companies. Reduced defense budgets following the Reagan administration, in combination with rising costs and overcapacity in the military industry, forced the aerospace industry to focus on affordability, rather than performance at any cost. Both of these programs now serve as bridges between academic learning and industry experience.

1.3 Background of Six-Sigma

Raytheon initiated a six-sigma effort three years ago (R6σ). As of September, 2002 - 62,000 employees had completed this orientation. A significant part of this effort is directed at making the organization *lean*, both through engineering product development and manufacturing on the shop floor. Most new employees are introduced to the R6σ during a short two-day course. A subsequent project will qualify the employee as an R6σ *Specialist*. Further projects can even promote an employee to the elite *Master Expert* status (34 employees)

Throughout different parts of the El Segundo facility, there have been different degrees of R6σ success. For higher-volume products, such as electronic radar built on the North Campus, there is a noticeable R6σ effort. For lower-volume products, such as space products on the South Campus, this effort has been more difficult to implement. While most of the initial R6σ work has been directed at leaning out shop floor activities, there has been less effort with product development involving engineers.

1.4 Background of Space Manufacturing

Space manufacturing differs from traditional manufacturing in that it requires not only high quality, but traceability of this quality. This traceability is often referred to as a "space trace." For reference, a six-foot, 150-pin cable will have a half-inch ring notebook full of information tracking its production. This information will contain all build procedures, suppliers for each part, verification that all tools passed inspection tests, and signatures of every person who touched either the planning or the cable itself.

There are two reasons for this space-trace. The *first* is a need for high-quality. Because satellites are inaccessible after launch, they must be manufactured to remain maintenance-free. Failure of these satellites could subsequently compromise national security. By tracking all parts and components used in the manufacture of the satellite, it is hoped that a high standard of quality can be maintained. The *second* reason for the space-trace stems from the high cost of each satellite. Throughout its life (design, build, launch, use), some of these satellites may reach upwards of one billion dollars to operate. While there are redundant systems onboard each satellite, it literally takes an act of Congress to use these backup systems. As such, it is important to trace the likely cause of the problem to the manufacturer to help determine the solution before switching to a backup system. If a satellite does fail, traceability becomes an important way to document fault, and possible fixes for these expensive machines.

1.5 Project Setting and Motivation

The original project description involved exploring product development for a proposed *Space Based Infrared System* (SBIRS) space project. Raytheon lost the proposal for this project one-week before my arrival, and the internship was transitioned to a lean assessment of the space side of Raytheon. Raytheon management sought three objectives from my visit.

1) **Determine areas of improvement**. The initial period was spent exploring the corporation and asking individuals where they thought improvement was possible. A list of people was developed across different levels in the organization including representatives from both engineering and operations. While the organization itself is large, we sought to narrow the scope of the project to one area.

2) **Document present status.** Within this project area, document how procedures are completed presently. Benchmark these processes with other operations both within the El Segundo facility and among other Raytheon facilities.

3) **Suggest room for future improvements.** Within the targeted project area, suggest ways in which the processes could be improved using both R6σ methods and procedures developed outside of Raytheon.

4) **Implement changes.** In the defined area, initiate the changes needed to meet these improvements. While previous three objectives would take much time, implementation would be perhaps the most difficult.

1.6 Project Approach

I used the following approach to conduct research for this project:

1) **Learn the organization.** The first month was spent in conversation with people throughout the organization. Interviews were established with representatives from both operations and engineering, targeting different hierarchical levels of the organization. This helped me become familiar not only with the area for study, but other areas throughout Raytheon.

2) **Determine an area of focus.** The cable assembly area was chosen, in part because of its smaller size and in part because many other programs used it. It was thought that problems in the cable lab might be representative of larger problems in other areas of Raytheon.

3) **Learn and document the area of focus.** Six weeks were spent within the cable assembly shop, both observing procedures and participating in the builds of test cables (non-flight).

Conversation with assemblers, planners, and engineers helped determine the build process of a cable.

4) **Identify areas of concern and areas of opportunity.** Various literature and resources were used to determine potentially beneficial changes, and other areas that might prove difficult with a lean transformation.

5) **Benchmark against other processes.** The author explored other areas within Raytheon to benchmark both within the El Segundo site and the greater Raytheon community.

6) **Recommend a lean road map.** Although this road map would be tailored to the cable assembly lab, recommendations should be applicable to other shops within Raytheon. Part of this lean road map would include future work, which could be implemented by future LFM interns.

7) **Initiate the transition.** Changes would be made to the cable assembly shop. While these changes would be tailored to the cable assembly shop, in a broader context they could be applied to other parts of Raytheon. This would be perhaps the most difficult part of the internship, and would involve both training assemblers in lean manufacturing, and overcoming resistance to implementation of a new system.

2.0 Definitions and Problem Statement

2.1 Lean Manufacturing Origins

Lean finds its origins in four well-known, but often forgotten principles: [Walton, 1999]

1) The goal of a business enterprise is to create wealth for its owners by creating value for its customers
2) Resources are limited – they must never go to waste
3) Intensifying competition demands that all business enterprises continuously improve by endlessly striving for ever higher quality, ever lower costs, and ever faster response times
4) People are intelligent and motivated to do a good job – give them the right tools and adequate authority, and they will not only do their jobs well, but they will also make improvements on their own initiative

Lean manufacturing was first implemented by Toyota, in what was termed the "Toyota Production System" (TPS). TPS was an ideology that sought to eliminate waste by producing only what was wanted by customers. Surprisingly, Toyota opened its factory for visitors to study its different production methodology; one such group of people came from MIT. The International Motor Vehicle Program (IMVP) coined the term lean production in response to what they saw as a radically different approach to mass production, through their book The Machine That Changed the World. Here they witnessed not only changes in the layout of the factory, but a dramatically different way of thinking in both management and employees.

Lean manufacturing goes beyond the physical factory floor. Much of lean manufacturing depends on a flow of information between the manufacturer, and both customers and suppliers. The more visible this flow of information is, the better the manufacturer is at producing only what the customer wants. For example, consider a pencil factory where customers may specify between different pencil types. Perhaps paint color on the pencil is one option. While a traditional assembly-line manufacturer may try to build different pencil colors to stock in hopes that future customers would prefer their forecast, a lean manufacturer would build these pencils to order, carefully delivering customer preferences upstream to the supplier. The paint supplier would then mix and deliver paint to the pencil factory as customer demand dictated. A simple, yet effective, example of this flow of information is seen in the MIT developed "Beer Game," where a pretend factory produces a product (could be beer) with different levels of upwards information flow allowed among different teams [MIT, 1960]. The result of this game (typically) is that the team with the highest degree of information flow also has the least amount of inventory in their system at the game's end, which allows them to accumulate the highest profit.

2.2 Fundamental Tenants of Lean Manufacturing [Womack & Jones, 1996]

Lean manufacturing really means delivering exactly what the customer wants, at the exact time the customer wants it. While there are many different ways to deliver this, Womack and Jones devised five fundamental tenants to describe lean manufacturing:

1) **Value**: providing for the customer the right product for the right price, at the right time.

2) **Value Stream**: the set of actions that bring a product through the business phases of problem-solving, information management, and physical transformation

3) **Flow**: seamless movement of only value-creating step

4) **Pull**: allowing the customer to define and pull the product rather than forcing, or pushing, a product upon the customer

5) **Perfection**: continuously and relentlessly improving the value, value stream, flow, and pull in business operations

2.3 Sources of Waste

Lean manufacturing seeks to eliminate "muda" – or waste. This waste can be categorized into seven generally accepted categories, listed below:

1) **Correction:** Redoing a report, repairing a part or redoing a service

2) **Overproduction:** Running unneeded copies

3) **Motion:** Taking more steps than necessary to complete a task

4) **Material Movement:** Material being routed through many steps

5) **Waiting:** Waiting to do work or parts waiting to be worked upon

6) **Inventory:** Old office or business supplies that no longer have value but are still being stored

7) **Procedure or Process:** Redoing things because of a cumbersome procedure

While this project sought to address each of these sources of waste, some types of waste are more prevalent in space manufacturing. In particular - correction, waiting, inventory, and procedure/process were the most likely candidates for lean improvements. This was not an environment where parts were built to stock – rather, when a part was manufactured there was inherent waste in operators performing rework, correcting mistakes or changes in customer requests, waiting for parts/inspections, inventory building up in the shop waiting for these parts, and non-uniform procedures and processes required to build these kits.

2.4 Lab 7

After two months of initial work, I decided to investigate ways to improve the operations of the cable assembly shop, also known as *Lab 7*. This area was primarily responsible for building cable harness assemblies that attached different modules within a satellite, although it also served to build other components when work was scarce. The layout of the lab was essentially a job-shop. Every assembler owned an individual work station, with enough tools to build the entire cable. Work stations would become quite disorganized, as there was little room left to build the cable with all this excessive equipment. Figure 1 shows a typical work station in this production system, along with an example of what a typical cable looks like (wrapped around the microscope). Implementation of a single-piece-flow would create more useable space by removing a significant amount of unnecessary equipment for each assembly step.

Figure 1 Work Cell

Figure 2, below, shows the tool arrangement before and after implementation. Before implementation, operators were given all tools necessary to complete all operations. After implementation, only necessary tools were stocked at specific build stations.

Figure 2 Tool Drawers Before & After Implementation

The shop was also a good place to demonstrate the positive potential of worker empowerment. Lab 7 was managed by two supervisors, who choreographed all work throughout the shop. When an operator finished a cable, or came upon a problem, they were instructed to report it to their supervisor before proceeding. Thus, the flow of the shop was very much controlled by the supervisor. Operators had little visibility of upcoming projects or what other assemblers were completing throughout the shop – and had no ways to contribute new ideas into the operations of the shop.

Finally, Lab 7's small size fit the parameters of the project well. It was small enough (~12 operators) to complete the transition within the seven month time frame, but seemed representative of other parts of Raytheon. The assembly itself was fairly straightforward. Each cable was built in a similar fashion, requiring little material beyond connectors, back shells, sleeving, pins, and wire. This allowed outside visitors to learn the entire build process quickly, and understand how the transition would improve both quality and efficiency. This simplicity in assembly also served as a role for other parts of Raytheon - if lean manufacturing could exist anywhere in Raytheon, it had to be able to exist in cable assembly. What worked in Lab 7 could then be transferred to other parts of Raytheon.

2.5 Problem Statement

The project sought to transition Lab 7 from operating as a job shop, to having a more efficient single-piece-flow production system. Instead of building an entire cable at one location, cables would proceed to different work stations throughout the room, where different parts of the cable would be assembled. Instead of every operator owning all types of tools, tools would belong to stations – and only those needed would be located there. If an operator came across a problem, they would be empowered to first try to solve the problem themselves, before looking to the supervisor. The production system would be designed such that assemblers would be encouraged to introduce changes they thought might increase the efficiency of the shop. A move away from a job shop would increase both efficiency and quality by forcing assemblers to work together, sharing a common fate across different cables. No longer would a cable belong to one person – it would be up to the entire assembly team to make sure all cables leaving the shop had the same high quality.

The project involved first designing this production system within the existing layout of the room. Cable assembly was broken into distinct operations, which were isolated to different areas. Flow through the shop was then mapped to maximize simplicity and to minimize the total amount of travel each cable would have to undergo. Finally, the design was implemented in the room – smaller in the beginning, and larger as subsequent trials proved successful. With this new flow, unique work stations were designed to produce each step of cable production.

3.0 Single-Piece-Flow Design

3.1 Assembly of Cable Harnesses

Cable harness production is mainly a craft. An operator assembles each harness by hand, without the use of any automation. Although there are variations, the majority of harnesses produced in this lab contained 2 or 3 ends. Assembly operations could be performed in any sequence, as long as inspection points were not covered up. The general order of assembly is shown below in Figure 3.

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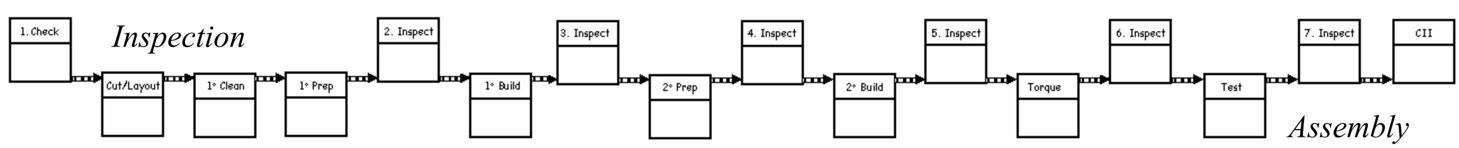

<u>Assembly:</u>

Cut/Layout – cut wire to length; layout wire according to engineering diagram; bundle/label wire types
1° Clean – primary clean/bake operation for wire – done within the cable shop
1° Prep – [for primary end] strip wire; crimp ends; ground shielding if necessary; make samples for pull-test
1° Build – [for primary end] insert pins into connector; install braiding
2° Prep – [for secondary end(s)] strip wire; crimp ends; ground shielding if necessary; make samples for pull-test
2° Build – [for secondary end(s)] insert pins into connector(s); install braiding; continuity testing
Torque – torque back-shells; torque screws
Test – resistance testing

<u>Inspect/Verify:</u>

Inspect: must be performed by an inspector
Check: may be performed by anybody

1. **Check** – make sure parts are correct in kits; traceability for parts
2. **Inspect** – pull-tests (initial & final); pins correctly crimped; shielding properly soldered
3. **Inspect** – pins correctly installed into connector; shielding correctly installed
4. **Inspect** – pull-tests (initial & final); pins correctly crimped; shielding properly soldered
5. **Inspect** – pins correctly installed into connector; shielding correctly installed
6. **Inspect** – final inspection
7. **Inspect** – damage inspection from testing, staking of bolts
8. **CII** – *Complete Item Inspection* – look at traceability, QA involved, all signatures present, tooling

Figure 3 Order of Assembly

Typical assembly involves first cutting wire to a length slightly longer than needed. Contact pins are then crimped onto the ends of each wire, which are sequentially pushed into a rubberized connector. A back-shell is attached to the connector, and wire shielding is fitted over the wires. The secondary ends are then prepped in a similar fashion, crimping contact pins which are then stuffed into additional connectors. All mechanical parts are then torqued to specification, and the cable is usually sent through a cleaning operation, depending on the customer requirements.

Throughout the build process, inspections are required by certified inspectors. The purpose of these inspections is to test both the quality of the assembly and calibration of tools being used. While many of the inspections are visual, some are quantitative. For example, weights are hung from each wire to make sure pins stick into the connector, and test samples must be made for each crimp tool that is used to check that the crimping strength.

3.2 Value Stream Mapping

Perhaps one of the first requirements in a lean implementation is identifying what is valuable within a process. Often this is done with a formal value stream map. A value stream map is a lengthy endeavor, requiring the input from many people. Value stream mapping includes first performing a value stream analysis where the entire process of a system is laid out. This analysis is then usually depicted in a graphical form that can be understood quickly by others. From here, it becomes important to identify which processes are wasteful, and which are "value added." Figure 4, below, depicts a high-level value stream diagram for cable production at Raytheon. Of this whole processes, perhaps "wire layout," "assembly," and "bake oven" are seen as valuable to the end user. The other processes can then be defined as either enabling or non-value added.

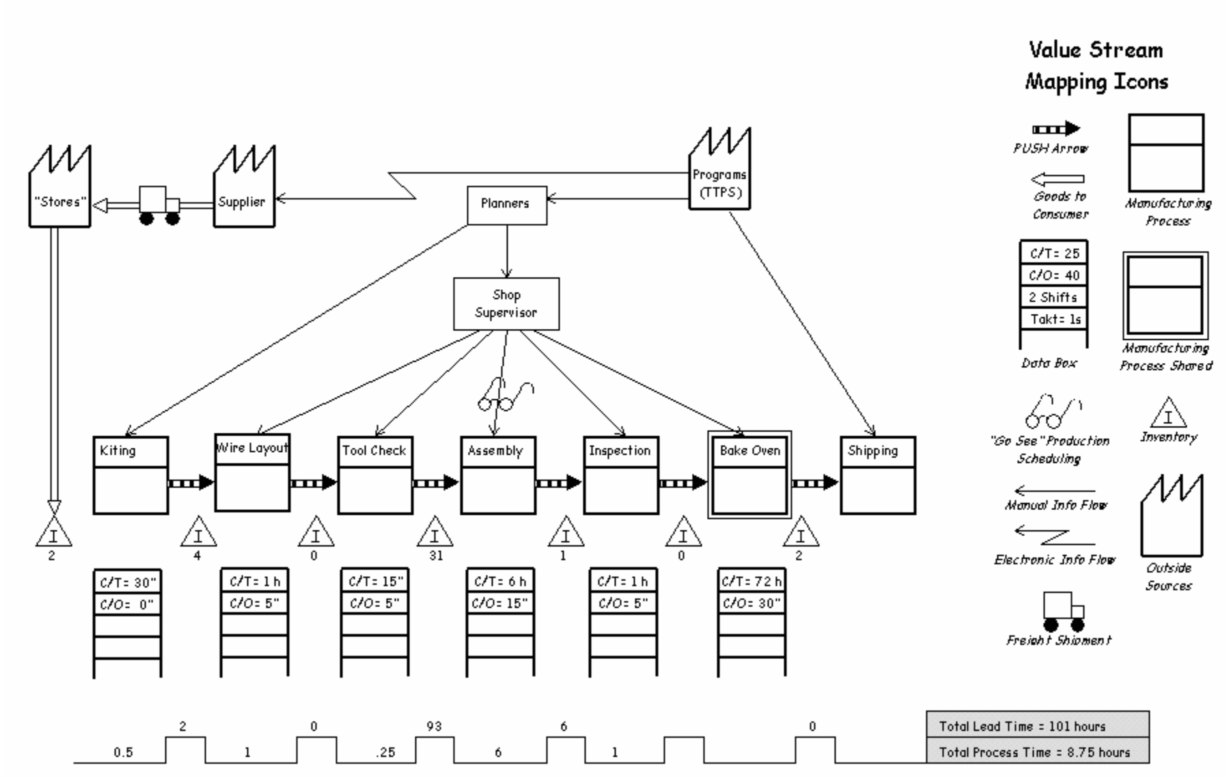

Figure 4 Value Stream Map

3.3 Enabling Processes

Enabling processes are those that do not add value, but are necessary to produce the end product. An example of this would be kiting each individual project before starting assembly. The customer sees no value in this step, and there would be no difference in the customer's view if this step were omitted. However, in order to produce the cable there must be parts, and these parts need to be found and accumulated together. Enabling processes tend to be good places to implement lean practices. While it is true that parts must be gathered in order to make a space cable, perhaps there is a better way to do this besides placing each in a box. Perhaps sources of parts could be located near the operator, thereby minimizing the amount of work that needs to go into creating a kit. Changing enabling processes frequently require a shift in corporate culture, which makes these types of changes long and difficult to implement..

3.4 Value Added Processes

Value added processes are the steps by which value is added to the product. The best example of this is the actual assembly of the cable. As the cable is built, there is value created from an inexpensive bunch of wires, pins and connectors. Typically, the customer recognizes these as necessary steps. Innovations into value added processes make great 6-sigma projects. These projects tend to be close to the operator, and often the operator knows how to best implement changes to make the processes more efficient.

3.5 Waste Processes

By definition, waste processes add no value to the customer and should be eliminated all together. For example, if Figure 4 was looked at in more detail perhaps there may be several cleanings that take place on the cable. Are each of these cleanings needed? Or is the final cleaning performed at the same level of quality as the others? If there is no added value to pre-cleanings, then they should be eliminated from the system. While waste processes are often easy to identify, they can still be difficult to eliminate. Many wasteful steps are in fact well intentioned, and originate from a localized vision of the problem. Perhaps the different cleaning processes were determined before the introduction of new cleaning systems that can remove all contaminants at the end of the build process. While it seems logical to the end user that intermediate cleaning steps could be eliminated, perhaps the additional cleanings were written into contracts, determined before the new cleaning system was available. In this case, eliminating the intermediate cleanings would also require approval from the end customer – the assembly shop could not simply stop intermediate cleanings, even if they knew they were redundant.

3.6 Required Tooling & Material Inspections

There are significant differences in the amount of freedom an operator has is crafting different cables. Most noticeably these differences arise between kits that are bound for product testing, and those bound for flight. At one extreme, a small proportion of kits are "build to print" – where the operator is not given a set of instructions, but rather just a print and parts list. At the other extreme are flight kits, which specify not only material – but specific tooling to be used on each kit.

There are few automated tools used in space manufacturing, and the assembly of cable harnesses required none. Wire is cut by hand, with shears. Shielding is stripped with standard wire strippers, and heated "hot-weezer" strippers. Contact pits are crimped with semi-specialized tools, and inserted into connectors by hand. In all, assembly of cable harnesses can be accomplished with roughly 20 different hand tools.

There is a large difference in the required inspections for each kit. While flight kits may require a pin-retention test on each assembled wire, a test kit may only require visual inspections. Despite this difference, however, both test and flight kits are typically built to similar standards.

3.7 Takt Time Consideration

Part of this project involved breaking the production of a cable into smaller discrete steps. In a typical single-piece-flow line, there must be consideration to an appropriate takt time for each step. In a strict single-piece-flow line, all steps must take an equal amount of time. As each step is finished, the product is passed from operation to subsequent operation, until finished. If any step is longer than the others, this step will become the bottle-neck of the process and become the determinant of cycle time.

Because single-piece-flow depends on each step having the same cycle time, it works best when there is little variation in the product. Unfortunately, there were large differences in the complexity and amount of assembly required on different cable harnesses. There were rarely duplicates of any cable, and because of this it was not possible to create a strict single-piece-flow production system. In the system created, some pieces were allowed to progress faster and slower than others. For example, a kit in production could be placed on hold for an inspection or parts, while other cables would jump ahead of this cable in line. Progression was determined by a first-in-first-out (FIFO) system of work in process. If a cable was taken out of production for unexpected inspection or delay in parts, other cables would skip ahead of this cable. When the cable was ready for work, it would be inserted back into the production line where it was last taken out.

Thus, it was important to create a high-degree of flexibility into this work production system. Flow could not be constrained by different takt times involved in different complexities and variations of cables.

3.8 Operator Flexibility & Limitations

Operator flexibility is rooted in lean production systems (Womack, 1990). Above all else, it gives employees more control over the operations in their workplace. Responsibility is shifted from a central authority figure to the employees, where is it hoped that by giving employees the necessary authority and set of skills "the team members will be more committed to their jobs and ultimately more committed to accomplishing their team's objectives" (Klein, 1994). Thus, work is managed at the employee level, and the destiny of the workplace resides more with the employees. This philosophy is rooted in the thought that those closest to the problems are often the most qualified to solve them.

Single-piece-flow works best when trained operators are flexible in different operations. Flexibility allows an operator to work on different processes, depending on where help is needed. For example, consider Figure 5 below – a production exercise I taught to the assemblers during the internship *(using extremely lean funding!)*:

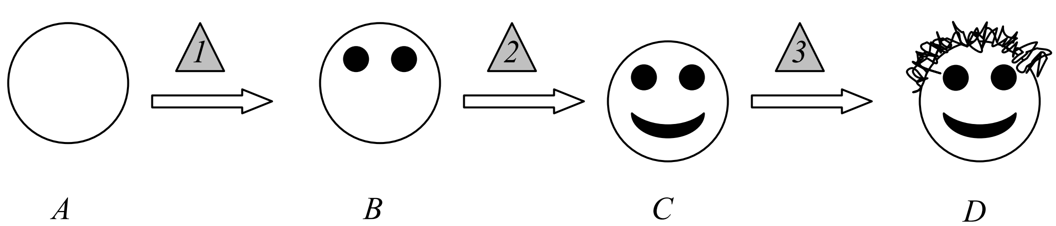

Figure 5 Smile Face Assembly

Even through a simple exercise like drawing smile faces, the advantages of operator flexibility become clear. In this example, the line will move at the slowest operator's rate. Assume each operator *A, B, C, D* can draw at rate *a,b,c,d*. If operator *C* was slowest, production would move at rate *c*, and WIP would accumulate at kanban *2*- designated by a triangle. Operator *D* would be starved for work, and would become intermittently idle. Assume operator *B* is the fastest, but was cross-trained to draw the smiles along with operator *C*. Now, operator *B* could help operator *C* when idle – thus reducing operation *C* as a bottleneck. Ideally, if all operators were cross-trained in all functions, the line would be able to move at the average rate of all operators combined. Thus, operator flexibility serves to increase the pace the production line can move at.

Unfortunately, the workforce in the cable shop tended to have a high turnover of employees. Much of this was due to the expansion and contraction of work; as work loads decreased assemblers would be transferred to other labs - often not returning. During a period of expansion, assemblers would be transferred into the assembly area, and the numbers of operators could actually double or triple. At the end of my internship, there was even speculation of adding an additional shift to accommodate an anticipated increase in work. This rapid expansion had two effects. First, operators needed training, which was often given by area supervisors. When supervisors performed this duty, they had less time to spend managing the lab. Second, new workers often had lower quality than those who were experienced. Both of these effects could be minimized if an operator was trained incrementally on different steps of production. A single-piece-flow system would allow for this, where operators would master one step of cable assembly before moving onto another – instead of learning the entire assembly at once. The area supervisor would spend less time training, as they were only teaching a single operation at a time, giving them more time to manage the lab.

Because of its importance, operator flexibility should be introduced as an incentive for promotion among new employees. Operators should progress from basic operations to higher skilled operations. Not only does this provide an incremental way of learning, but it also provides a clear path for new employees to improve their position within the company.

3.9 Design of the Production Lab

The design of this production lab was determined to maximize flow throughout the shop. At the same time, however, the design had to accommodate frequent disruptions to flow - taking into account tool, material and assembler inspections. Listed below are these disruptions that program customers required to be designed into the system:

1. *Ability to Submit Incomplete Kits* – Virtually no kits entered the assembly area with all needed parts. A substantial (1 month) supply of kits was constantly on hold. Thus, the production system needed to be able to accommodate kits entering and exiting the system.
2. *Inspection Points* – Both space and test kits need to be inspected and verified by inspectors.
3. *Tracking of Kits* – Assemblers, inspectors, and planners needed to know where kits were throughout the system. Because the production would no longer be

choreographed by the area supervisor, another system needed to be implemented to communicate locations of kits.

4. *Flexible Work* – Although cable production composed the bulk of work, this lab was also used for customized work, such as soldering components onto circuit boards. The lab needed to retain this flexibility.

Additionally, this production lab was to be designed into a "brown field" site, where production was already taking place. Of the total available space, much of this was unusable as it was filled with equipment from the previous production lab that occupied the space. Pictured below in Figure 6 is the layout of the available space. All rooms in the picture were available to use, however the production lab was confined to the larger center room. The smaller squares in this room represent monumental support columns that required five-foot clearance because of fuse boxes installed on them.

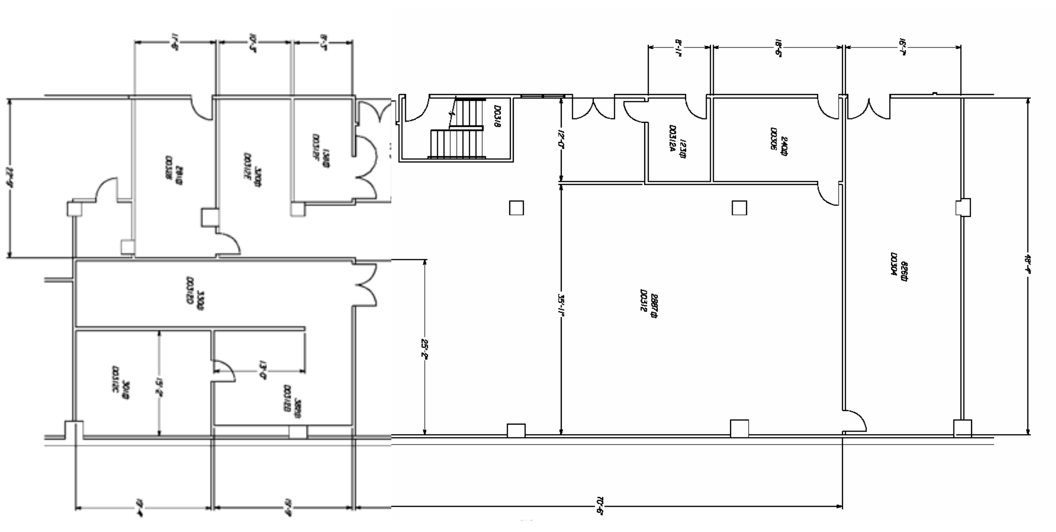

Figure 6 Room Layout

When I arrived, production was already taking place in this larger room. Ideally, this space should be easily configurable, with tables on wheels and drop-down electrical and air power. However, like the support posts, the work tables were also monuments – each one being powered from installed bases through the floor. This made reconfiguration of these tables difficult, and a decision was made early in the project to work with the existing layout – rather than push for a new one.

The room layout consisted of thirty-two desks, stacked in eight rows. Each of these desks was a separate work station, theoretically enabling a force of thirty-two assemblers. Each desk was equipped with tools to handle all tasks, from cable harnesses to circuit boards. While it was important to leave part of the room with this flexibility, the majority of the room would be transformed to make only cable harnesses. Figure 7 shows the layout of the new production lab.

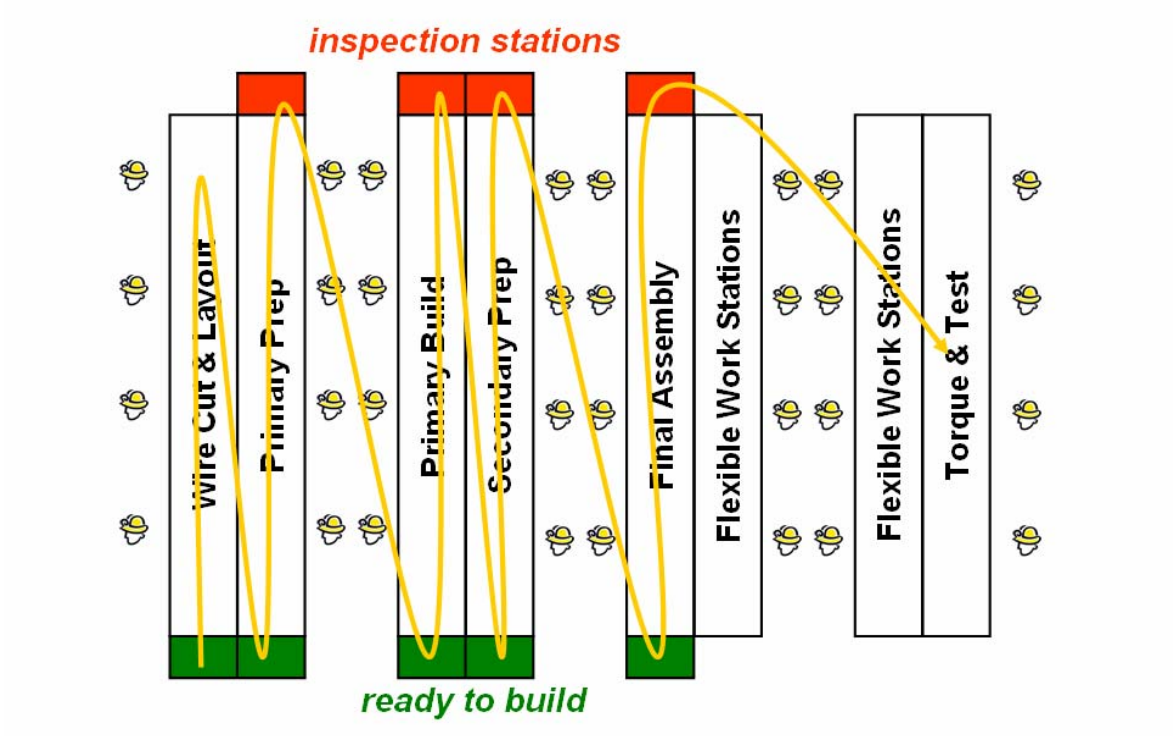

Figure 7 Production Flow

<u>Key</u>:

1. Green-filled rectangles on the bottom of the diagram represent WIP kanbans, with work that is ready to build.
2. Red-filled rectangles on the top of the diagram represent WIP kanbans, which are waiting for inspections.
3. Helmeted heads represent individual desks.
4. The yellow arrow represents flow of work throughout the room.

3.10 Six Distinct Assembly Areas

Six distinct areas of assembly were identified. Each of these areas was chosen such that assembly could proceed as far as possible, without covering prior work that needed to be inspected. Thus, instead of inspections throughout the build, inspections could now be aggregated into four groups. The benefits aggregating inspections were two-fold. First, operators could complete assembly without having to wait for inspections. Inspections would be done away from the production areas, freeing the operator to move onto another task. Second, by aggregating inspections into kanbans, there was no longer a need to staff a permanent inspector in the assembly area. Now, a visiting inspector could inspect waiting work, moving completed inspections to ready-to-build kanbans. The following were determined to be distinct operations:

Wire Cut & Layout:
- Wire is cut to length.
- Cut wire is tied together in the rough layout of the cable.

Primary Prep:
- Wire on the first end of the cable is stripped of insulation.
- Contact crimps are fitted onto each stripped wire.
- Appropriate grounding is performed, either with solder or crimps.

Primary Build:
- Back-shell is fitted onto the primary end.
- Contact crimps are pushed into connector.
- Ground shielding, and protective sleeve are placed over wire.

Secondary Prep:
- Wire on the second end of the cable is stripped of insulation.
- Contact crimps are fitted onto each stripped wire.
- Appropriate grounding is performed, either with solder or crimps.

Secondary Build:
- Back-shell is fitted onto the secondary end.
- Contact crimps are pushed into connector.
- Ground shielding, and protective sleeve are placed over wire.

Torque & Test:
- Back-shells are tightened to required torque
- Final continuity & resistance tests

3.11 Visual Factory

This shop would now operate without central control from the area supervisor. While the supervisor would still be on-hand to solve problems, her function would no longer include coordinating work through the shop. This was a difficult transition for both the supervisor and assemblers, and as such there needed to be a clear system to follow.

Work moved throughout the shop visually. Assemblers managed their work by looking in "ready-to-build" kanbans, whereas inspectors took work from "inspection" kanbans. The process is outlined in Figure 8 below.

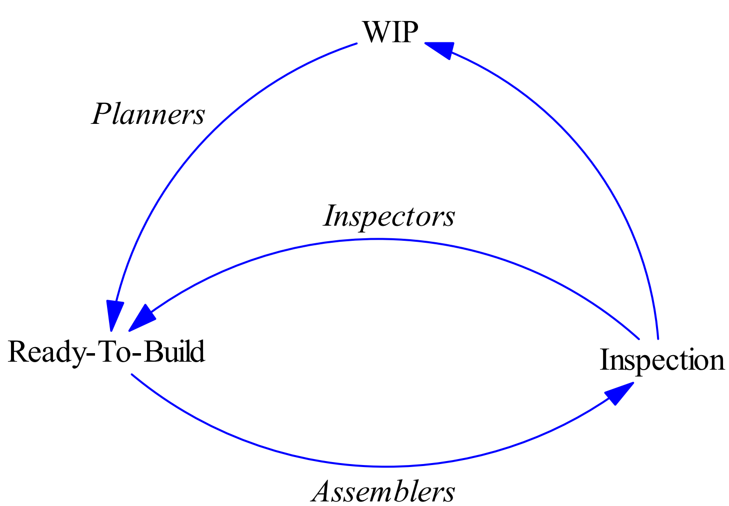

Figure 8 Production Process Flow

Work flow is visually depicted in previous Figure 7. This flow, however, was quite discontinuous as individual cables would be placed on hold for both parts and inspections. In other words, if three cables started in a particular order they would not necessarily be finished in that same order. Because of this, kanbans were established to store and signal work that needed to be completed. Kanbans were placed before each order of operation – both for inspectors and assemblers. If work was ready for either assembly or inspection, it would be placed in these kanbans, to be used in a first-in-first-out system.

Often, work was pulled out of assembly and inspection to be placed on hold. Kits would exit the system to be placed on hold racks. Throughout this process, it was important to track where each kit was in the assembly lab, so it could easily re-enter the assembly operations. Five sets of racks were designated to hold kits waiting for each order of assembly: wire cut, primary prep, primary build, secondary prep, and secondary build.

Each kit that entered the assembly lab was given a tag with the kit number on it. Throughout its life in the assembly lab, this tag would designate where the kit was in the shop on one of two kanban boards. The first board was for *work in process*. As a kit moved from one assembly step to another, its tag would reflect this. When a kit was placed on hold, its tag would be removed from the WIP board and placed on the *hold board*. While this did help to organize kits throughout the shop, it provided valuable signaling to visiting planners and engineers. These boards would allow any person from outside the shop to quickly identify where a particular kit was within the shop. A planner could now place needed parts in a kit, remove the kit from hold, and replace it back on a kanban where it would be ready for assembly. Figure 9 pictures two of the kanbans boards in the shop. Attached to these boards were magnetized cards representing each kit, that assemblers would move to represent where each kit was within the shop. If the kit was being worked on, it would be somewhere on the *work in process* board, whereas if it was on hold it would be on the *on hold* board.

Figure 9 Kanban Boards

Thus, through the addition of kanbans, hold shelves and two marker boards, work could now move throughout the production lab without central coordination from the area supervisor. There was no longer a need for a central figure to find work for each assembler throughout the day – assemblers knew where to find this work themselves. In addition, much of the communication was now done through large visual aids that tracked the progress of each kit.

3.12 Reduced WIP

Taiichi Ohno, father to the Toyota Production System, identified excess inventory as “the greatest waste of all.” The TPS is based on efficiently producing exactly what the customer wants, at exactly the right time. This is done by keeping WIP low at all levels. TPS’s “just-in-time” delivery system ensures that only needed parts are delivered to the factory at just the right time, and within the factory there is little room for WIP to accumulate.   Traditional manufacturing philosophy prioritizes high utilization of equipment, in hopes of reducing unit production costs. With this philosophy, however, waste actually increases. Excess inventory is common, and products are often built before the customer has determined what they want.

Space assembly has similar WIP problems. The cable harness shop typically stored at least one month of WIP, in various stages of completion. The primary reason for this WIP was missing parts. Cables would be started, without all the necessary parts available for the complete build. Assemblers would start the project, knowing that they would have to stop work before finishing. It was not uncommon for a cable to sit in the production lab for over a month, waiting for parts. There were two reasons for this, one was organizational – production benchmarks included both when the project was started and finished. Thus, programs were rewarded for starting a project early, even though it would wait as WIP in the production lab. Programs also perceived that starting a project earlier would allow the cable to be finished faster when the necessary parts did come. The other reason for this waiting was that orders for parts tended to be small – often single pieces. Connectors were typically not stocked by the vendor, and required unique keying that were individually made by the vendor. Lead times on these parts alone could exceed one month. Within this one-month parts window, it was not atypical for customers to change the requirements of the cable – either removing contacts, or adding additional wires.

Managing WIP requires a significant amount of work. Fred Stahl's investigation of process control at John Deere actually discovered that the slogan "inventory is evil" was promoted throughout their St. Louis manufacturing plant (Stahl, 1994). Not only does WIP increase the chance of rework from changing orders, but it requires significant effort and space to manage. In the cable lab, inventory racks covered just about every wall. With a month of backlog, one of the supervisor's principle jobs was to organize and track where each partially completed cable was, and why it was placed on hold. There is a high cost when storing a significant amount ofWIP, and this was especially true when WIP was stored in expensive static-free clean-rooms.

Although the scope of the project did not reduce this WIP, instead it was managed into the production system. WIP racks were organized at the ends of each production line. If a kit did not have enough parts to continue onto the next operation, it would be stored and tracked on a WIP board (Figure 9). Thus, location of WIP signaled at what stage each kit was in. Within these racks, each kit was then clearly labeled what program it belonged to, and the reason it was on hold. Any person in the assembly lab could now easily understand what stage each cable was at, freeing the area supervisor from tracking these kits. A planner could now populate kits with necessary parts, and place the kits back in production. Because this information was all shared by visual cues, there is no need for the supervisor to document individual cable status.

3.13 Flexible Line Layouts

We designed this production flow from a "brown field" site, and our layout was not ideal. Electrical and air outlets were cemented into the floor, making it difficult to change the layout. In Figure 8, our process takes a "Z" form, in that material is moved back to the starting point at the end of each step in the process. This results in wasted material movement and operator handling. In addition, it takes away from the ultimate goal of a visual factory. Figure 10 below, shows the factory layout found at Harley Davidson. "Cellular layouts can be much more flexible than product layouts and much more efficient than process layouts" (Hanna, 2001)

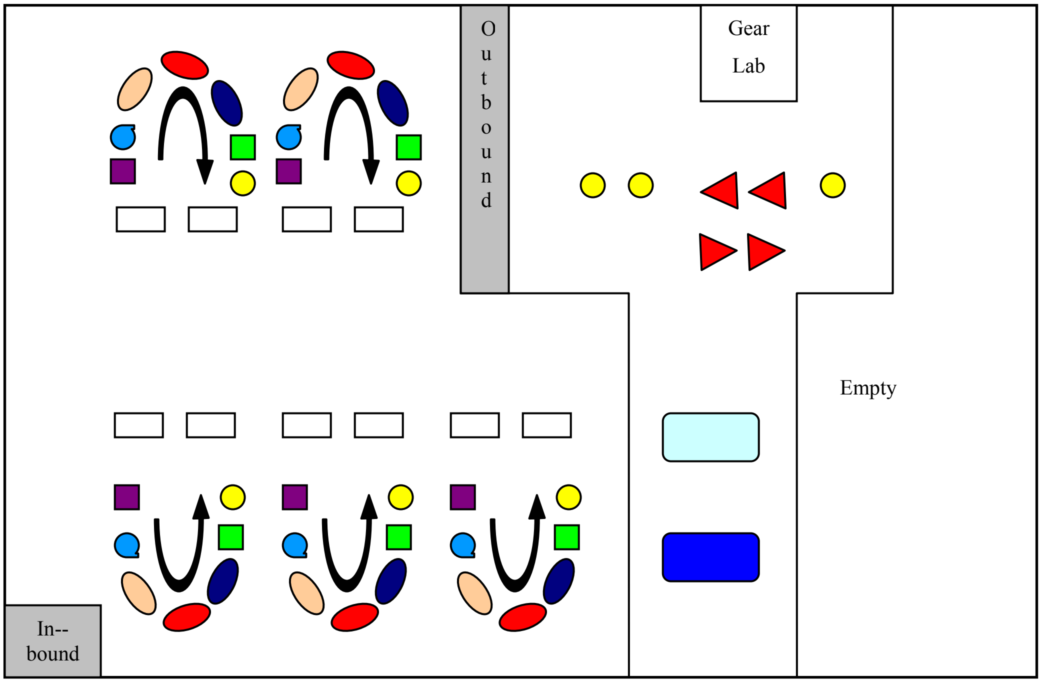

Figure 10 Cellular Layout at Harley Davidson[1]

While many productions lines are straight, "a straight line is not always best." (Krajewski, 2001). The production cells in Figure 10 above are U-shape, but variations may include L, O, and S shapes. This allows an operator to move between tasks while a machine is in operation. Throughout each operation, the worker is in visual contact with all pieces of equipment, and is able to spot errors quicker. Wallace Hopp found the following benefits to U-shaped production cells (Hopp, 1996)

1. One worker can see and attend all of the machines with a minimum of walking
2. They are flexible in the number of workers they can accommodate, allowing adjustments to respond to changes in production requirements

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[1] From: Peter Reid, *Well-Made in America*, New York: McGraw-Hill, 1990.

3. A Single worker can monitor work entering and leaving the cell to ensure that it remains constant, thereby facilitating just-in-time flow
4. Workers can conveniently cooperate to smooth out unbalanced operations and address other problems as they surface.

In fact, there are many variations to the u-shape production cell. Successful variations, however, maintain flexibility by situating operators close together, so they can freely communicate and share work. Richard Chase recommends the following examples of flexible vs. non-flexible line layouts in Figure 11 below

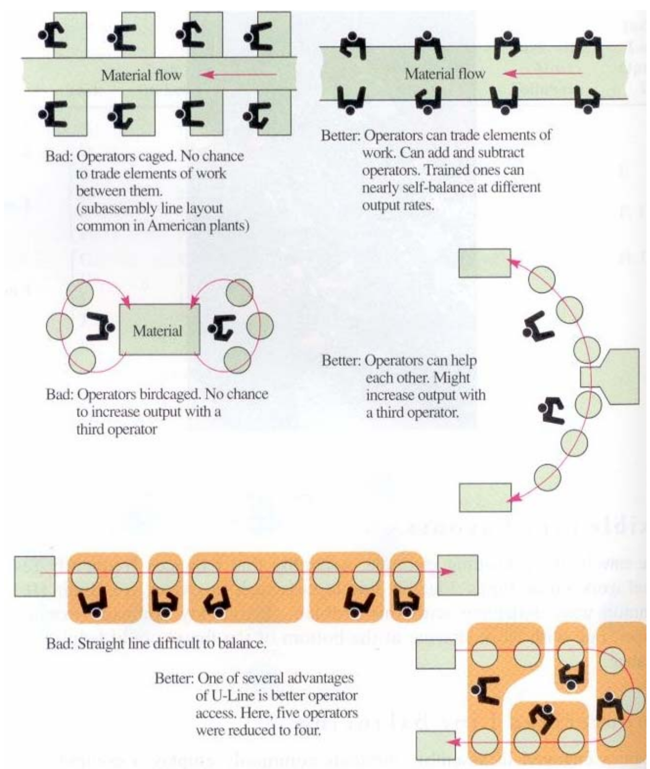

Figure 11 Flexible Line Layouts[2]

[2] From: Hall, Robert W. *Attaining Manufacturing Excellence,* Homewood, IL: Dow Jones-Irwin, 1987.

4.0 Discussion

4.1 Continuous Improvement Among Assemblers

One underlying belief in lean production is that many of the process improvements can be found among the workers. Thus, it becomes important to empower these workers to suggest and implement these changes. Consider Southwest Airlines, and their ability to maintain 15-minute gate turnarounds by decentralizing the management of gate workers to best determine how to load and unload planes quickly. While Raytheon has a culture of employee empowerment, none of the assemblers had gone through six-sigma training in the shop. Part of this project was to establish a system that promoted worker empowerment to make decisions and changes to the production system.

TPS initiated the idea of the andon-cord, where any worker could pull a cord that would stop the entire production system. While stopping an entire production line is expensive, Toyota found it even costlier to produce cars with defects. Similar problems are found in space manufacturing – parts, planning, and engineering often have similar mistakes across similar cables. In a job-shop with assemblers working individually, there is little communication among employees when problems have occurred. In one instance, we found incorrect planning of sleeving length across different kits. Sleeving was cut at the same length of each cable – this was too short. In fact, when sleeving is placed around the cable bunches, it shrinks in length as its diameter increases. By the time one assembler discovered this mistake, not only was sleeving cut for several cables, but it some cases it was already in place with the other end partially assembled. Fixing this problem required placing another sleeve on the cable and pulling pins out of the secondary end.

In an improved system, assemblers would discover this problem and relay it to other assemblers, before other cables are built. This can be accomplished by producing products in a single-piece-flow rather than in batches. Building kits in series, instead of parallel, should help to alert problems before they are worked on by other people. This should be particularly true when similar operations are performed in close proximity to each other. If an operator discovers a problem, it should be easier to diagnose and alert other close-by assemblers. Working pieces in series also pushes some kits in a batch further along than others. Mistakes become more visible further down the production flow, allowing corrections to be made to kits that have not been started yet.

4.2 Upwards Knowledge Flow

Space products require much control over quality. As such, production and procurement tend to be highly regulated. Much of the time this is a customer requirement, in that certain quality checkpoints are written into contracts. There is also a baseline quality that Raytheon would set to all its cables. This need for quality control often conflicted with a perceived need to regulate activities that occurred in the lab. Figure 12 below is the general process flow Raytheon uses for design and production.

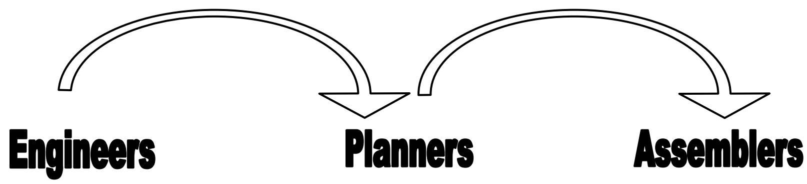

Figure 12 Process Flow

In this process flow, there are clear handoffs between each group downstream. Engineers will first design drawings, specifying parts chosen and schematics of the part. This is then given to planners who source these parts and create detailed instructions for building. Finally, the parts and instructions are passed to assemblers who create the product. While clear avenues exist to flow information down, there are few formal channels to feed information back up. Further complicating this is the fact that often planners and engineers are located in different buildings, sometimes in different geographic locations.

This structure likely exists from a need to control quality within the manufacturing environment. There are few decisions an operator can make outside of the instructions given on the cable. While this type of organizational design does ensure items are built according to engineering specifications, its rigidity hinders learning and improvement from assemblers.

4.3 Operator Inspections

In an ideal flexible production environment, all operators can perform all tasks. We were fortunate in that by transforming from a job-shop into a single-piece-flow all operators were already familiar with all parts of assembly. However, operators were still not allowed to perform inspections on any of their work. Figure 13 below represents the decision tree for inspections involving inspectors (Cowab, 1996):

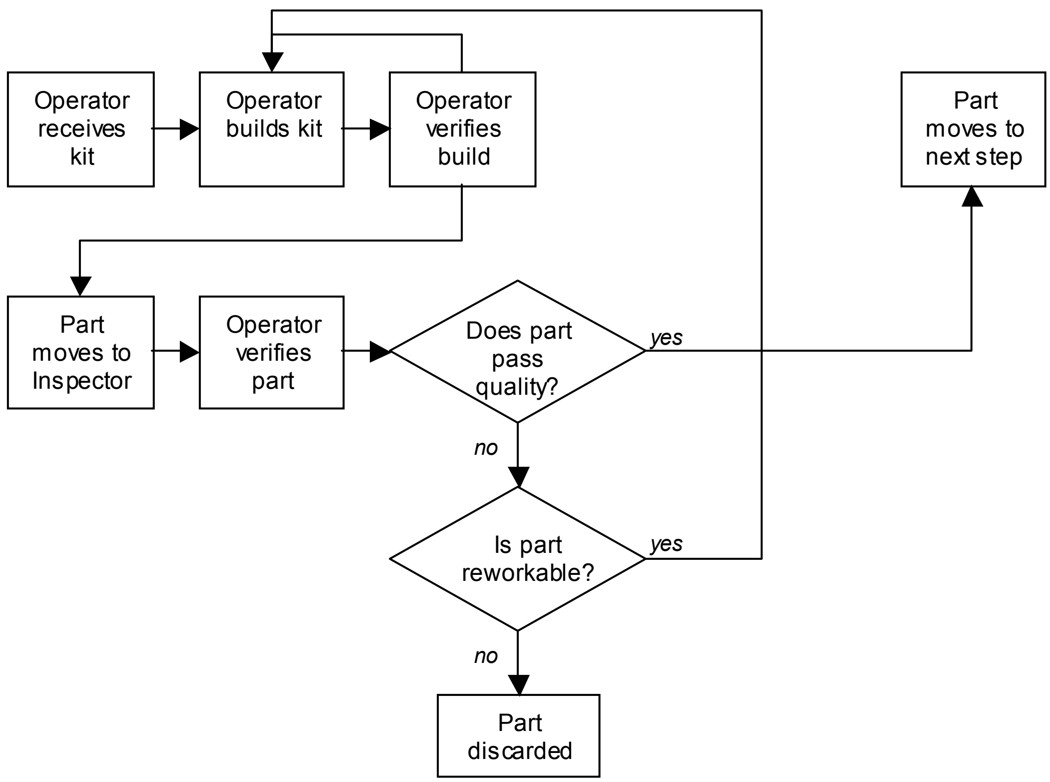

Figure 13 Work Flow With Inspectors

Perhaps part of this type of organizational process is the belief that greater control over processes increases quality. This is actually contrary to lean philosophy. While greater control may baseline quality to a certain level, it forgoes any increases in quality that may be gained from empowering a workforce. Stacey Cowab found four major benefits to having operators perform inspections, rather than inspectors (Cowab, 1996)

1. Provide immediate detection of man, machine, and process errors
2. Provide an alternative to 100% in-line inspection by quality personnel
3. Provide greater incentive to manufacturing personnel to identify part status correctly

4. Provide positive feedback to operators to prevent errors from re-occuring

This type of work flow is represented in Figure 14 below.

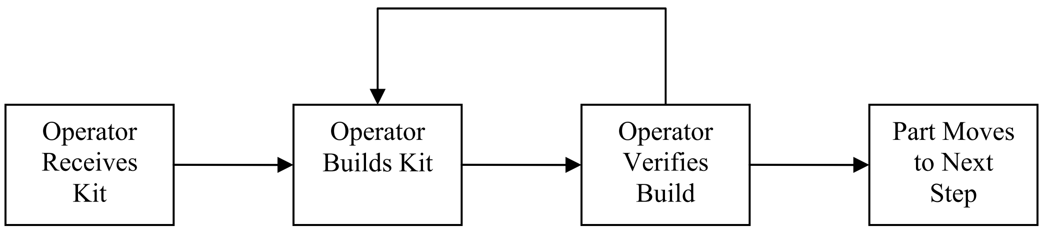

Figure 14 Process Flow Without Inspectors

In a lean environment, operators are aware of the quality checkpoints. Problems are caught early on at the source, instead of being shelved for later use. For example, consider a required pin-retention test that must be performed by an inspector. Before an operator begins to assemble pins to stripped wire, they must make several samples to be pulled on a tester that gauges the strength it takes for the pin to be removed. These tests are performed routinely by the assemblers, and quantities of samples build up for an inspector. Typically, the operator has started this operation before the inspector has had a chance to run the test – sometimes they are even done with all the wires. If there is a problem with this test, not only has the operator wasted time completing work that will need to be redone, but they run the risk of scrapping the entire cable if rework requires cutting off faulty pins that make the cable too short. If the operator was able to perform this test, they would be able to check their tools before starting work and would correct any problem before starting work on the cable.

Consider also what the operator learns from the test. If it fails, why did it fail? Was the wrong wire used, were the proper contacts inserted into the kit, or was the crimp tool set to an incorrect setting? If the operator has moved onto another task, it may be impossible to track back the problem. If the problem was only an improperly set crimp tool, it may be impossible to discover this if the tool is now being used in another operation. Can the mistake be traced back to either an engineer's or a planner's misunderstanding? If so, this responsibility should rest with the assembly team to implement improvements in design, not with an inspector who checks work.

Perhaps a middle road would be to replace the inspector with operators who checked other people's work. This would serve two purposes: maintain quality close to the problem, and ensure an extra set of eyes that the inspector would have provided. By having an operator perform the inspection, there would continue to be learning among assemblers. Assemblers would be trained in what to look for in an inspection, and this sharing of work would foster learning through examples of other operator's work. Perhaps an operator would learn a better way to complete a task, or spot a problem and teach the other operator the correction. Maintaining the different operator would also ensure the extra set of eyes to make sure there was no oversight. Although this should not be the case, at times reading from diagrams requires interpretation. Perhaps it is difficult to read a number, or maybe there is simply confusion at to how a certain wire should be connected. In either case, having another person inspect the work would help to minimize these errors.

Finally, operator inspections should serve to increase quality by increasing morale among the assembly team. Stacey Cowap noted that among the driving forces in this program was "peer recognition" as "a source of pride." If operators are given the tools and "freedom to make the call" (Cowap, 1996) in inspections, they are that much closer to their work. They are now fully aware of the checkpoints for quality, and are now themselves entirely responsible for the quality in that part.

There are potential benefits to operator certifications, however it requires a commitment from the company. Results are typically only seen in the long-run, after significant investment in employees. The assemblers must be trained on what to look for in inspections, and must pass some type of certification that meets customer requirements. This also requires a certain investment in changing the culture of the organization – by shifting power to the operators. While many firms may find this hard, it is likely the hardest for aerospace companies that require highest quality, as demanded by their customers. It is possible, however. On a visit to another Raytheon plant in Goleta, CA I found they were almost exclusively performing operator inspections. While they did commercial customers, whose need for quality may be lower, it was apparent this system did work.

5.0 Organizational Change

5.1 Strategic Design

Raytheon is organized into two functional basic groups – product design and production. There is much overlap – especially in the space products facility I worked in. Because space production is essentially one-time builds, design and production were often blended together. I worked in a unit called the Consolidated Manufacturing Center. The CMC was a production group, which focused on building some of the common components across different programs. Some examples of work included wiring harnesses, circuit cards, and sensors.

This group acts as an internal supplier to different programs. In fact, the CMC is in competition with outside vendors, as programs are free to source parts outside of Raytheon. There is a distinct customer relationship between the programs and the CMC. The CMC depends on the programs sourcing products from them – and would not be able to exist without them.

Programs themselves are quite independent. They share few resources with other programs, and operate from totally separate budgets. Much of this is by design, as work is often classified. However, at times this makes the production labs disjointed. Programs will stock the production lab with the material needed to produce their products, and are quite reluctant to share these resources with other programs. For example two programs may share the same type of wire, but they will be stored on two different spools. If one programs runs out of wire, programs are extremely reluctant to share this resource with others. Most likely an order will wait for parts, even if the parts are available from another program.

This type of organization is difficult for the production labs. Inventory is stored it the shop, but managed remotely by outside programs. Demand for work tends to be cyclic, as programs submit projects in groups. In addition, there is little intellectual sharing among programs. Programs tend to staff their own engineers and planners, who devise the schematics and work instructions for each kit. This all tends to disrupt production – inventory is high in the lab, most of the racks store partially completed kits, and similar engineering/planning problems come up across different programs. At times, the lab seemed more of a body shop than a production shop. People would be shifted between different labs to accommodate for changing levels of demand, and there seemed to be little feedback from production back up to engineering and planning. Figure 15 below represents the organizational structure I found:

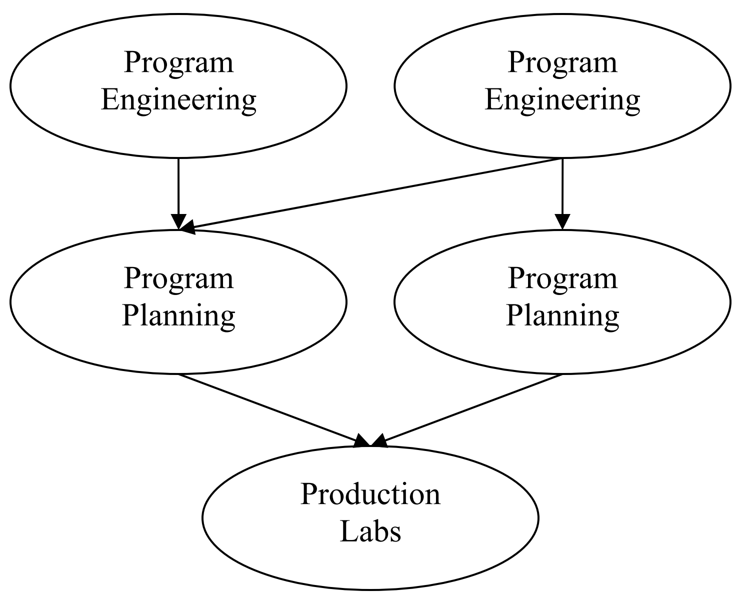

Figure 15 Organizational Structure

Within the operations community, however, there was a push towards lean operations. While there was a large difference in the degree of *lean* among different parts of the organization, some areas of space manufacturing were quite efficient. These areas were shown as examples to both outside customers, and to other parts of Raytheon. Using these areas as reference made it easier to pitch trying similar efforts in the cable assembly lab.

5.2 Cultural Lens

One of the fundamental lean tenants involves empowering those closest to the assembly, with the ability to implement process changes. This proved to also be one of the hardest transformations to implement. The cable lab was very much a hierarchical system, where a central supervisor would direct work throughout the shop, and coordinate which assembler would assemble each project. If there was a problem, the supervisor should be contacted first. Success and failure of each assembly rested with individual assemblers. As such, there was little incentive to share best practices with other assemblers. In fact, there was some evidence that just the opposite was true. In a lab where each assembler worked on separate cables, only the supervisor played the role of process improvement - critiques among peers were not encouraged.

John Hoppes found a similar situation in Texas Instrument's Defense Systems & Electronics Group's (DSEG) McKinney board shop (prior to being acquired by Raytheon). In 1989, board orders were falling, product mix was rising, and customers were becoming more demanding. Although DSEG had undertaken some process improvement steps, they still had 14,000 boards in WIP – with cycle time hovering around 9 weeks. In response, DSEG decided to implement self-directed teams within different areas of operation. Similar to the cable assembly lab, DSEG’s circuit card shops were choreographed by a central supervisor. It required a total of 6-9 months for these different areas to transition to self-directed teams, where assemblers had both the ability and confidence to make decisions on their own.

In fact, my presence as a “Leaders for Manufacturing” fellow posed some initial concerns. There was a group of people that believed that manufacturing did not have a place in space products, and any attempts to try to integrate lean manufacturing would result in repeating failures from the past. This skepticism actually gave the project momentum to try to prove that lean manufacturing can exist, as a space assembly plant. In fact, there were examples of lean manufacturing already in the plant. In particular, one of the radar labs had made significant progress in producing a visual factory, where parts flowed through a production line with specific work cells. Thus, this project was touted as an experiment to prove that manufacturing could exist.

The project itself was well suited to use an example that space manufacturing can exist. Whereas many of the space assemblies are highly complex, a cable assembly is relatively easy to understand. If any part of space assembly could be leaned out, it was this area. Its relative ease to understand also helped sell the idea to others – people could quickly understand the basic assembly and grasp how lean improvements could make the system better.

In fact, this project was intended to serve as an example of how lean production could exist in space manufacturing. As we began the implementation, we produced large signs around the assembly area informing others of the project: “Caution – Lean Implementation Underway.”

There was also much done inside the lab to describe the transition underway. New marker boards tracked projects throughout the room, and signs were affixed to new work stations. Even the drawers were loaded with new tools to signify a new method of production.

6.0 Future Work

6.1 Reduction in Approved Parts List

While a shift towards lean starts on the factory floor, it must include all factors that go into production. I expect that many of the difficulties the production lab had, hinged upon the large number of parts that were available for use. This was quite evident by looking at the volume of wire stored in the shop. In all, there were over one hundred different types of wire on hand for different projects – so large, in fact, that a good deal of the wire could not even fit into the room that was designated to hold it. Closer inspection of the wire revealed that many of these different wire types were quite similar, varying only in the color of the insulation. This diversity arose from only *five* different wire gauges that were used in producing these cables. A similar amount of product diversity was also found in the high number of different pin and backshells used.

The first benefit in an approved parts list would be to simplify build instructions. Because assemblers are rotated throughout different labs to meet cyclical demand, operators are often unfamiliar with instructions. Much time is spent by the operators simply interpreting drawings and instructions in planning. Fewer parts to choose from should reduce the variety of different operations possible, making it easier for a new operator to learn assembly.

Second, a diversity of parts drives lead times for ordering. Throughout my internship, the shop had over a one-month inventory of WIP waiting for parts. While wire was relatively easy to source, backshells and connectors were not. They were built to individual specifications, with lead times that often exceed one month. If an operator damaged a part during assembly, the component ran the potential of sitting on a WIP shelf for another month.

Third, product diversity drives procurement costs. Programs that do not share parts cannot drive discounts from suppliers. More importantly, it is expensive to track and store these different parts – especially when these parts are stored in static-free clean rooms. If programs are all ordering different parts, there is little reason to stock these components as inventory within the production facility itself.

6.2 Production Lab Stores Inventory

Significant improvements could be realized if the production labs were able to stock parts themselves. Currently, the production labs stock no material themselves, outside that which is ordered by the programs. Kits were actually placed on hold for such parts as replacement bolts and pins.

Imagine, instead, a production environment where the assembly shop maintains an inventory. Instead of sharing nineteen common wire types across different programs, each program pulls from the same spool – and is charged for whatever they use. Common parts, like screws and pins, are kept in stock such so that cables are never kept on hold for "nuisance parts."

If this system was combined with a reduced approved parts list, programs would no longer have to order these parts individually. There would be no month-long lead times for parts, and all documentation required for tracking products would already be attached to each part. Planning of these parts could now happen at least a month later, and would better reflect the needs of the system. Instead of ordering a connector with ten empty slots for later changes, engineers would have a better idea of what the cable was connecting and could adjust their requirements.

6.3 Planners As Part of Operations

Now imagine a system where planners are included on the factory floor. Instead of being hired out of program offices, they are attached to the production lab. Mistakes on the floor would be easily tracked back to these planners. Because programs are sharing planners, identical mistakes across different programs would be reduced. The production lab could now provide more services to the program offices, as programs would no longer have to staff planners.

Including planners as part of operations would be a significant step towards becoming lean. While changing factory floor operations was a good initial step, production in a space assembly environment is ultimately determined by planners. An in-house planner could make better use of an improved layout, and their local presence would make it easier for assemblers to communicate with.

7.0 Conclusion

This project was a success: we were the first team to train hourly employees on 6-sigma, we started a self-managed line flow, we involved assemblers in the process, we transformed the both the shop floor and work cells, and we did it while removing $113,000 in equipment. Use of visual controls helped reduce WIP, reduce cycle time, while increasing quality through improved assembler communication. Figure 16, below, summarizes the milestones achieved, and was posted inside and outside lab 7.

Figure 16 Lean Milestones

I did not see the project through to completion and difficult phases were yet to come. Cultural change is always difficult and often takes a long time to fully implement – often years to fully develop. Fortunately, throughout the process both supervisors and assemblers were involved in determining these changes. This helped create other stakeholders in the process, who will continue the push for lean operations and assembler involvement. *Certainly this project would have been impossible, were it not for the willingness of the assemblers to try a new system, and the commitment from management to see the project through!*

8.0 Resource List

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