Driving a Lean Transformation Using a Six Sigma Improvement Process

By

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

Master of Science in Mechanical Engineering
Master of Business Administration

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Abstract

Successive transformations within manufacturing have brought great efficiencies to producers and lower costs to consumers. With the advents of interchangeable parts between 1800 and 1850 in small arms manufacturing (Hounshell, 1984, pp. 3-4), mass production in the early 1900s in automobile manufacturing (Hounshell, 1984, pp. 9-10), and lean production in the early 1950s in automobile manufacturing (Womack, Jones, & Roos, 1990, p. 52), the state of manufacturing has continued to evolve. Each time, the visionaries that catalyzed the transformations were forced to overcome the inertia of the status quo. After convincing stakeholders of the need for change, these change agents:

1. Established a vision for the future
2. Committed resources to attain that vision
3. Studied the root causes for current methods
4. Proposed a new solution
5. Implemented the new solution
6. Quantified the results and sought future improvements

This basic process to implementing change is remarkably simple yet incredibly powerful. By explicitly emphasizing the need for root cause analysis, the process recognizes that improvements will be transient if the root causes of prior problems are not fully understood and resolved.

When deploying a lean production system, an understanding of lean principles and tools is necessary but therefore not sufficient. Rather, implementing a lean production system should follow:

1. An analysis mapping the root causes of current production methods back to technical issues and the organization's strategic design, culture, and political landscape. Only by fixing the problems that led to the current production system can a lean transformation be sustained.
2. A detailed plan which achieves a transformation in both the organization and the production system.

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I am also grateful to the directors, staff, faculty, and students of the Leaders for Manufacturing Program at MIT. I cannot imagine a better place to learn. I can only hope that one day I will give back as much as I have already received.

Lastly, I thank my family for their love and patience. How truly lucky I am for all the opportunities I have been given. I do not thank you often enough.

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Table of Contents

Table of Figures

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1. Introduction

Barriers to the flow of information and materials will continue to fall as technology continues to feed the forces of globalization. Organizations that are nimble and efficient will replace those that are plagued with inefficient processes. To remain competitive in the years ahead, organizations must remove the waste that has accumulated in their processes.

Many companies have acknowledged that the principles behind lean manufacturing may hold the key to their survival. In its Production Operations Transition-To-Lean Roadmap, MIT's Lean Aerospace Initiative reduces the process of implementing a lean production system into simple tactical steps grouped into the following eight phases (Crabill, et al., 2000, p. 38).

Phase 0: "Adopt Lean Paradigm" focuses on establishing the need and commitment for change and communicating a vision
Phase 1: Prepare for the lean transformation. Identify an implementation team, strategy, cultural impediments to lean and metrics to gauge progress
Phase 2: Define the customer and the customer's needs. Establish targets for quality, schedule, and cost
Phase 3: Create a map of the current value stream
Phase 4: Synthesize a production system consistent with the future state. Calculate takt time, create a more suitable physical layout of the facility, implement visual controls, and incorporate preventative maintenance
Phase 5: Implement material flow
Phase 6: Implement pull
Phase 7: Continuously improve phases 2 through 6

This thesis contends that transforming an existing production system into a lean production system requires a commensurate transformation in the organization. Merely acknowledging the need for organizational change is insufficient. Instead, we must map the root causes of the waste within current production methods back to both technical and organizational issues. By fixing these root causes, the organization can sustain the gains it will achieve through eliminating the waste within its production methods.

Thesis structure

A brief description of this document's chapters may help clarify its layout.

While this lean initiative was focused on radio-frequency (RF) circuits called circulators, Chapter 2 briefly describes both upstream components and downstream assemblies. This product description may help the reader visualize the products.

Chapter 3 starts with a description of the problem. It continues with sections that describe the technical and organizational challenges that preclude a cookbook application of lean principles. Chapter 3 concludes with the hypothesis statement.

Chapter 4 describes the Raytheon Six Sigma™ process. This versatile process is often used to plan and implement change, because it is methodical in its approach to problem solving. It therefore serves as a convenient structure for the development of this thesis. In short, chapters 5 through 12 show the relevance and application of the six sigma approach to lean implementation.

Chapters 5 through 7 describe the first three steps of the Raytheon Six Sigma™ process. Even though these chapters are brief, the importance of these steps cannot be underestimated. Chapter 5 details the first step: "visualize." Chapter 6 describes the second step: "commit." Chapter 7 illustrates the third step: "prioritize."

Chapters 8 through 10 describe the fourth step of Raytheon Six Sigma™: "characterize." Since this step contains the root cause analysis of the status quo and the articulation of a future state, this step has been divided into three chapters. Chapter 8 characterizes production methods through a root cause analysis. Chapter 9 characterizes the organization using the Three Lens Model. Finally, Chapter 10 characterizes the future state.

Chapter 11 focuses on the fifth step: "improve." This chapter describes the steps required to implement the lean initiative.

Chapter 12 contains the sixth and final step: "achieve." This chapter reviews the project's results, assesses the validity of the hypothesis statement, and emphasizes the importance of recognizing contributors.

Chapter 13 opens the possibility of extending lean principles to the enterprise level. The chapter provides an overview of the benefits and requirements of attaining a lean enterprise. The chapter also emphasizes that many of the lean tools used on the factory floor are directly applicable to the enterprise level.

Chapter 14 concludes this thesis document with a discussion of next steps.

2. Product description

The Space and Airborne Systems (SAS) business unit of the Raytheon Company designs and produces a variety of products including active array radars for military aircraft. An array is the mechanism through which an antenna system forms transmit and receive beams. With an active array, the radar can electronically steer individual portions of the array to simultaneously navigate the airplane and track objects.[1] In some modes, this steering is accomplished automatically. With the previous technology, the radar steered the entire array via a mechanical gimbal. Therefore, pilots could not simultaneously track and navigate with the previous technology.

[1] For technical information, see: Stimson, G.W., 1998. *Introduction to Airborne Radar*, 2nd ed, Mendham: SciTech Publishing Inc, pp. 473 – 479.

Since active arrays provide pilots with a new and powerful capability, the military has decided to equip several kinds of aircraft with this new technology. To efficiently meet the growing demand for these arrays, SAS has committed to transforming its production methods from traditional batch-and-queue to lean.

Production of an antenna system is inherently a complex task involving thousands of parts. Removing waste from all levels of assembly is critical to ensuring that Raytheon can continue to offer technologically superior systems at competitive costs and lead times. Therefore, the company has started with removing waste from several levels of assembly that drive the overall system's cost and schedule. The focus of this lean project is to remove the waste within the production of RF circuits called circulators.

Description of product flow

Figure 1 below depicts the product flow, from lower level subassemblies to higher level assemblies. The following sections provide a high level description of these assemblies.

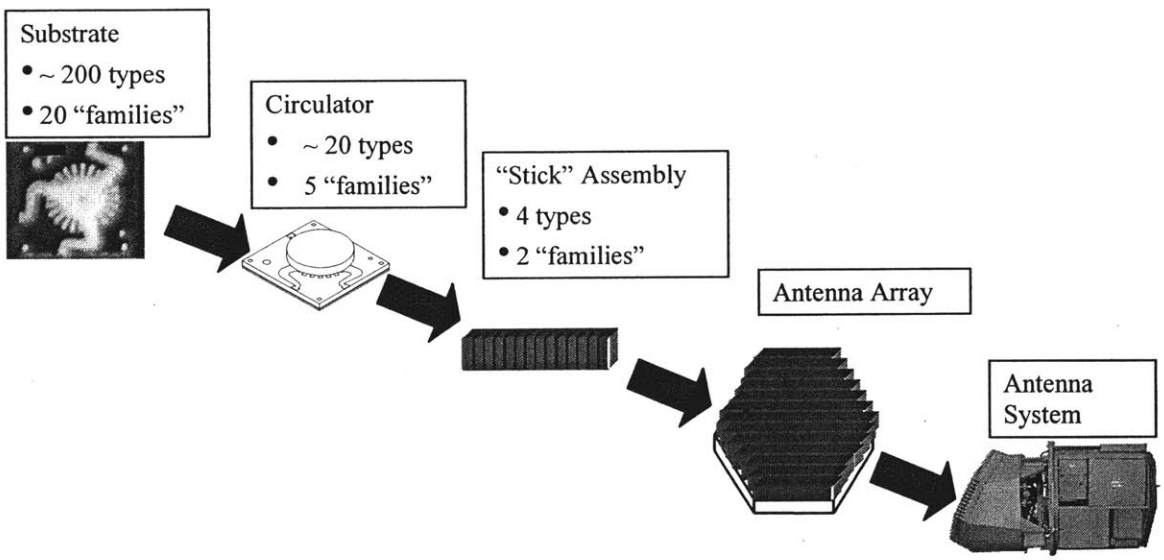


Figure 1: Substrate to Antenna System product flow

2.1.1 Substrates

Substrates provide the basic mechanical structure and interconnects for different kinds of RF circuits. Two hundred types of substrates have been produced, and they can be grouped into twenty families based on similarities within production methods. The majority of substrates are produced for microwave integrated circuits (MICs) and other RF assemblies. Only a small fraction of the substrates produced are integrated into circulators and related RF devices like loads, flints, and isolators. Each type of circulator, load, flint, and isolator uses a unique substrate.

2.1.2 Circulators

A circulator allows a single array element to both receive and transmit. When the antenna system is transmitting, circulators route RF energy from their transmit port to their antenna port. When the antenna system is receiving, circulators route RF energy from their antenna port to their receive port. By preventing high power RF energy from flowing from their transmit port to their receive port, circulators protect sensitive electronics that are designed for low power signal reception. Twenty different types of circulators have been produced, and they can be grouped into eight families based on similarities within production methods. Circulators destined for antenna systems are typically higher in performance than those used in other applications. These higher performance circulators are not made for their own profitability but rather for their importance in the functionality of more profitable antenna systems. Nonetheless, circulators are not commodity components.

2.1.3 Stick Assemblies

Stick assemblies are notionally shown in Figure 1. These assemblies are comprised of structural housings, circulators, other RF elements, and RF interconnects. Antenna arrays differ in size and shape, causing "stick" lengths to vary as well. As a result, the type and number of RF devices within each "stick" vary. This variability presents a challenge for manufacturing this assembly. Four types of "stick" assemblies exist and can be grouped in two families based on similarities within production methods.

2.1.4 Antenna Arrays

Antenna arrays are the conduit through which the antenna system transmits and receives RF signals. The four types of arrays can be loosely grouped into two families based on similarities within production methods. Each type of antenna array has been designed specifically for its higher level antenna system.

2.1.5 Antenna Systems

An antenna system using active array technology allows a pilot to simultaneously navigate the aircraft and track objects in the air and on the ground. Raytheon manufactures antenna systems using this technology for four types of military aircraft. These systems operate at different frequencies and differ in form factor. However, at a high level, all have functionally similar components and follow similar assembly and test processes.

3. Problem statement (Burning Platform)

The urgent need for change is often called a "burning platform" at Raytheon. The "burning platform" in circulator production stems from two challenges:

- Demand growth in antenna systems will approximately double the demand for circulators in one year, with continued growth expected thereafter. Keen on ensuring that resources are efficiently used, senior management will deny requests to double resources to meet a doubling in demand. Thus, production staff must eliminate waste and ensure that existing resources are efficiently used before requesting additional operators and machinery.
- Senior management has mandated a 50% cost reduction for certain programs in order to meet business objectives. These same business objectives motivate management to seek savings, including in circulator production.

With current production methods, circulator production staff cannot meet the demand growth and cost reduction challenges. Most stakeholders therefore accept the need for change. However, isolating the problems and implementing the appropriate solutions are not trivial. Solving the problem will require overcoming both technical and organizational challenges.

3.1 Technical challenges

In its future state, the circulator production system must contend with the following technical challenges:

- Use of Material Resource Planning (MRP) software which pushes work-in-progress (WIP) into production
- Production complexities which are created by reentrant processes, setups, and differing process flows
- High mix, low volume production which complicates scheduling and setups
- Growing demand which can shift bottlenecks
- New product development which reduces capacity for production
- Lack of standard work which introduces variability

3.1.1 MRP

One technical challenge is reconciling the broader organization's drive to use MRP with the desire to control WIP. MRP authorizes the release of kits into production based on a schedule and not based on the amount of WIP already in the system. WIP levels therefore grow and shrink without control in an open loop fashion.

3.1.2 Effect of reentrant processes, setups, and differing process flows

Standard lean theory is remarkably simple. It uses simple U-shaped production cells that build products at the pull of the customer. Production is based around takt time. We divide processes into smaller steps such that the cycle time for each step is less than the takt time. If demand changes, we update the required cycle times to meet the new takt time.

Unfortunately, three factors specific to the circulator manufacturing process preclude the direct application of this simple yet powerful theory: reentrant processes, setups, and variable process flows.

The circulator assembly process currently requires expensive capital equipment to place components and apply epoxy. Since it is not economically viable to purchase a machine for each step, circulators return to the same machine at several points along the assembly process. The result is a reentrant process flow that is also commonplace in semiconductor manufacturing.

Significant setup times and setup variability cause lot sizes to be greater than the ideal lot size of one circulator. Clearly, efforts to reduce setup times and reduce the effect of setup variability on circulator performance will enable the use of smaller lot sizes in the future.

Each family of circulators has a unique sequence of process steps. Therefore sequential jobs may compete for the same resource because they use resources in different orders. Figure 2 below illustrates:

a. The difference in process flows for two of the eight circulator families
b. The reentrant nature of the circulator assembly process (i.e. a few machines perform the vast majority of assembly steps). The number within each box indicates the number of times that resource is used when "Family 1" is produced. As we can see, some capital resources are used on four discrete steps. Labor is used in all fifteen steps.

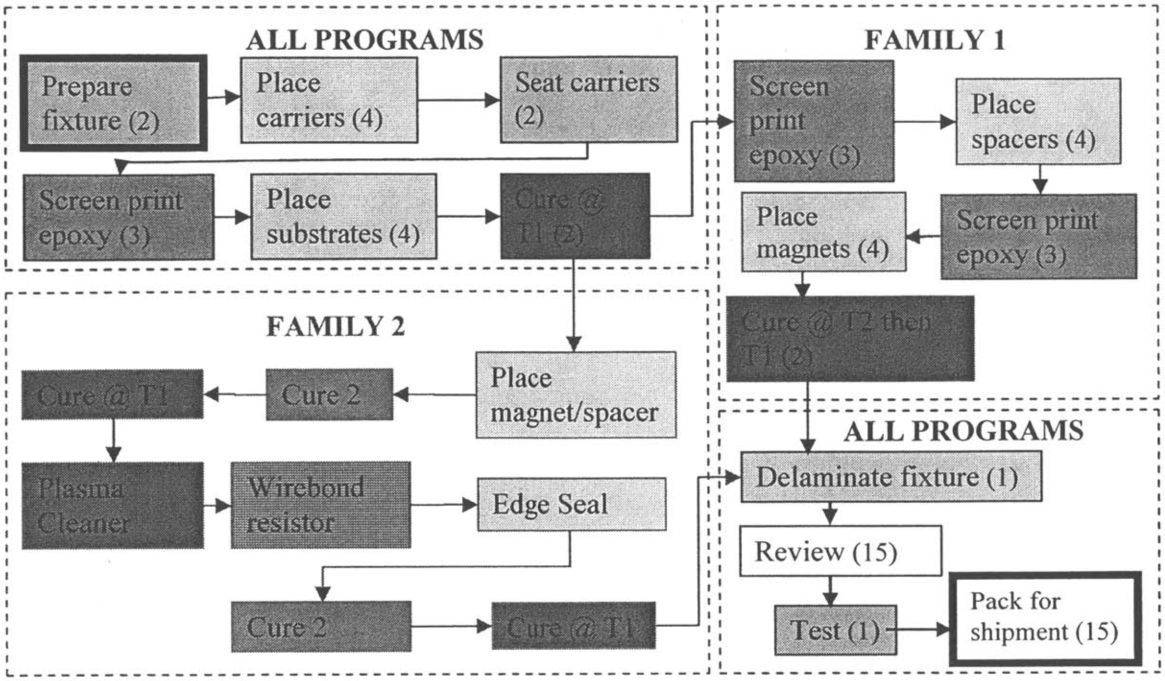


Figure 2: Circulator assembly steps

3.1.3 High mix, low volume production

Circulator production must also contend with the classical high mix, low volume problem. Presently, lot sizes vary by circulator family from a few hundred to a few thousand circulators. Demand for a given circulator type may be consistent (e.g. several lots every month), inconsistent (e.g. several lots every few months), or just sporadic. At present, between five and ten lots of circulators are produced monthly, and this volume will more than double in approximately one year.

3.1.4 Growing demand

Because of quickly growing demand, the number of resources required will vary by year. The standard work content and amount of WIP allowable on the floor will vary as demand varies.

3.1.5 New product development

To develop new circulators and new production processes, design and process engineers require production equipment and operators' time. Scheduling development time in advance is difficult because:

- Software programs can only approximate circulators' performance. Thus, circulators sometimes require iterative design, build, assemble, and test cycles.
- It is difficult to estimate the amount of time required to develop a new process to create a new circulator. All circulators do not follow standard processes.

- The lead time for circulator components and tooling is sometimes long and variable.

3.1.6 Lack of standard work

Standard work only exists for some processes. For other processes, cycle times and quality standards can vary significantly. For example, differing definitions of "clean" currently result in a 300% variation in cycle time for a certain manually intensive cleaning operation.

3.2 Organizational challenges

Prior to the lean engagement, a highly technical engineering staff orchestrated the production of circulators and also developed new types of circulators. The engineering staff remains integral to the design of circulators and development of production processes. This staff also manages the customer relationships. Naturally, they feel great ownership over all aspects of circulator design and production.

The engineering staff also adopted batch and queue production because of its intuitive appeal. Large lot sizes appear to solve the perceived needs to:

- Amortize setups across a larger quantity of circulators
- Reduce the variability in component and epoxy placements
- Increase the up-time of all resources (not just bottleneck resources)

The engineering staff is vocally skeptical of lean manufacturing because lean manufacturing explicitly calls for lot size and WIP reduction. *Allowing certain resources to remain idle is a foreign concept and was not immediately embraced.* Since the engineering staff had met all customer cost and schedule requirements in the past, they remain unconvinced that a sudden emphasis on time-based production is critical.

3.3 Hypothesis

Understanding and addressing these technical and organizational challenges is essential to deploying a lean production system for circulators. While the eight phases of the LAI Production Operations Lean Roadmap contain all of the required lean principles and tools, the roadmap itself does not place sufficient emphasis on the prerequisite organizational change.

A previous student of lean asserted, "the transformation of an enterprise based on traditional mass production to lean principles and practices requires a major comprehensive change in behavior throughout the organization" (Tonaszuck, 2000, p. 15). The Lean Aerospace Initiative agrees: "Lean is not merely a set of practices usually found on the factory floor, but rather a fundamental change in how the people within an organization think and what they value, thus transforming how they behave" (Bozdogan et al., 2000, p. 7).

In essence, this thesis combines two existing building blocks:

- The importance of performing a root cause analysis
- The recognition that a lean implementation requires organizational change.

In short, an understanding of lean principles and tools is necessary but not sufficient to deploying a lean production system. Rather, implementing a lean production system should follow:

1. An analysis mapping the root causes of current production methods back to technical issues *and* the organization's strategic design, culture, and political landscape. Only by fixing the problems that led to the current production system can a lean transformation be sustained.
2. A detailed plan which achieves a transformation in both the organization and the production system.

4. Raytheon Six Sigma™

We cannot solve our problems with the same thinking we used when we created them.
- Albert Einstein[2]

The Raytheon Six Sigma™ change process serves as a useful tool in structuring the analysis, transforming the organization, and implementing the new production system. By using this structured process, change agents can be more confident that they will not omit critical steps.

While originally used as a statistical approach to quality control, the six sigma approach gained momentum when it was applied to general process improvement. The Raytheon Six Sigma™ process was developed from a variety existing corporate programs: the Texas Instruments Continuous Flow Manufacturing program, the Hughes Aircraft Agile program, the Motorola Six Sigma® program, and the General Electric Six Sigma program. Defined internally as a "knowledge-based process for transforming our culture to maximize customer value and grow our business," (Brassard & Ritter, 2000, p. *e*) the Raytheon's Six Sigma™ process shares many principles with lean manufacturing. For example, its principles are (Brassard & Ritter, 2000, p. *e*) :

- "Specify value in the eyes of the customer"
- "Identify value stream; eliminate waste and variation"
- "Make value flow at pull of the customer"
- "Involve, align and empower employees"
- "Continuously improve knowledge in pursuit of perfection"

At least one chapter in this thesis is dedicated to each of the six steps used in the process. These chapters explore the application of six sigma to the circulator lean transformation. A brief description of each of the steps follows:

[2] Source: http://www.brainyquote.com/quotes/quotes/a/alberteins121993.html accessed on March 14, 2004.

Step 1: Visualize the future state and establish a need, or burning platform, for change
Step 2: Commit key stakeholders who can enable success
Step 3: Prioritize tasks to ensure the efficient use of resources
Step 4: Characterize the initial state, perform a root cause analysis of desirable and undesirable effects, and then articulate a future state that incorporates solutions to underlying problems.
Step 5: Improve the system through implementing the proposed solution
Step 6: Achieve success and document the benefits realized and lessons learned

The graphic shown in Figure 3 illustrates the steps and the emphasis on continuous improvement.

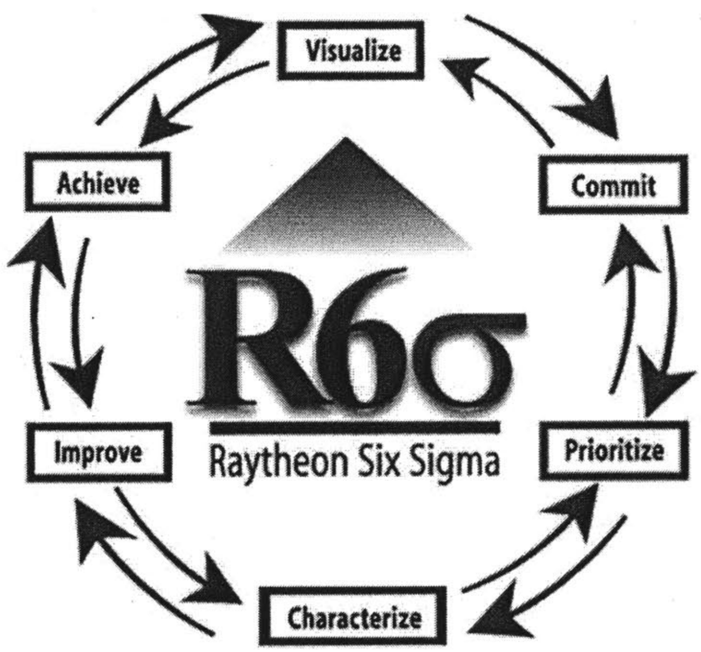
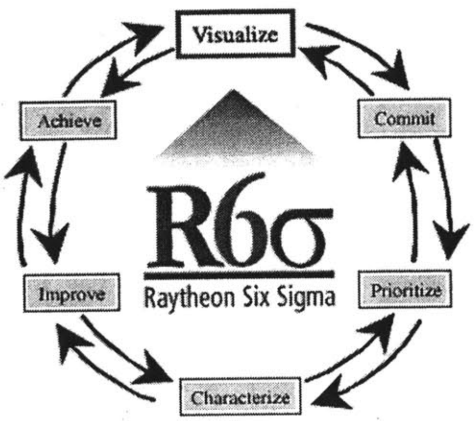


Figure 3: Raytheon Six Sigma™ process

5. Step I - Visualize

A rock pile ceases to be a rock pile the moment a single man contemplates it, bearing within him the image of a cathedral.
- Antoine de Saint-Exupery[3]



Prior to the lean engagement, SAS evaluated the state of circulator production. Assessors praised the emphasis on quality and the novel use of existing equipment to meet production demands. However, few lean tools were in place: visual controls were not posted, value stream mapping was not evident, standard work was not defined, etc. The assessors believed that a concerted lean engagement could help the facility reduce lead times, reduce WIP, and improve productivity.

Galvanized by their findings, our team established an initial vision: create a production system that reduces queue times by emphasizing material flow. We created a pilot program for one circulator program, in which operators focused on only one job. These operators successfully reduced the lead time from 16 manufacturing days to approximately 4 manufacturing days. However, since subsequent builds were not closely monitored, production discipline inexorably eroded. Long and variable lead times returned. High WIP levels returned as well. Some operators and support staff were unsure why change was even necessary. One operator asked, "If it's not broke, why fix it???"

A purely tactical solution may generate short term tangible improvements. However, these improvements will be temporary, if root causes of problems are not identified and resolved. However, by demonstrating that gains are possible, change agents build credibility. This credibility becomes important in designing and implementing the longer term solution.

Establishing a vision

"The notion that you can drive change to lean from the bottom is 'pure bunk'," declares one expert who has studied several lean transformations (Liker, 1998). Since a lean deployment requires getting "experts at doing things the old way to do things in a new way,[4]" senior leadership must not only display unwavering commitment but also be willing to consider changes in the organization. Responding to the need for a vision for future circulator production, the Directors of the Engineering and Operations organization co-authored a vision statement, articulated specific responsibilities for each

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[3] Source: http://www.brainyquote.com/quotes/quotes/a/antoinedes106018.html accessed on March 14, 2004.
[4] Howardell, Doug, *Seven Skills People Need to Create a Lean Enterprise*, p. 3 available at http://www.edi.gatech.edu/Lean/Lean_Articles/leanarticles-sevenskills.cfm

organization, and defined metrics and incentives consistent with long term goals. Their vision statement was crafted to include both strategic elements to provide context and tactical elements to provide direction (Chatterson & Wallace, 2003, p. 3):

"The Circulator Manufacturing Lab will:

- Use a predictable production system based on lean principles
- Use scheduling and quality tools to load and monitor the production system
- Integrate the value stream through synchronizing upstream and downstream production schedules
- Provide capacity for engineering development work during regular business hours
- Optimize resources (e.g. capital, people, floor space, etc.)"

In consultation with key stakeholders, the directors redefined roles and responsibilities for all the people critical to the production area's success. Since people naturally resist change that threatens their power and influence, these new roles were carefully crafted to emphasize the possibility for career growth. The document and related discussion focused on the need for continued collaboration between the Engineering and Operations organizations and stressed that written descriptions were neither limiting nor static. In communicating a vision and altering the organization's structure, the two directors fulfill both halves of Nanus' Leadership Formula (Nanus, 1992, p. 156):

$$\textit{Vision} + \textit{Communication} = \textit{Shared Purpose}$$

Equation 1: Nanus' model for shared purpose

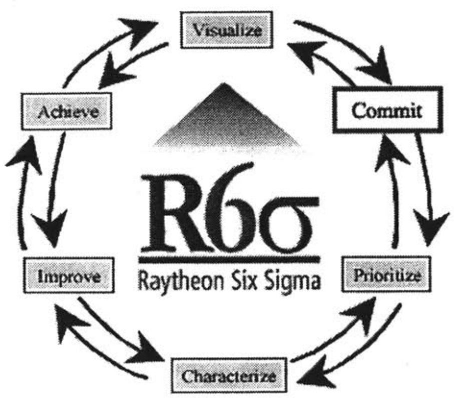
$$\begin{gathered}\textit{Shared Purpose} + \textit{Empowered People} + \textit{Appropriate} \\ \textit{Organizational Changes} + \textit{Strategic Thinking} \\ = \textit{Successful Visionary Leadership}\end{gathered}$$

Equation 2: Nanus' model for visionary leadership

A vision alone cannot accomplish a goal; instead, the organization must identify and commit people and resources. The next chapter explores this second step in the six sigma process.

6. Step II - Commit

Unless commitment is made, there are only promises and hopes...but no plans.
– Peter F. Drucker[5]



By committing the existing team of Operations and Engineering staff to attaining their joint vision, and then equipping that team with the necessary financial resources, the two Directors maximize the probability of a successful lean deployment. The two Directors themselves demonstrated their willingness to provide guidance and resolve conflicts by attending critical meetings and offering to help remove obstacles to the lean deployment. The Directors also made funds available to solve problems that might obstruct the lean implementation. In one instance, the team secured a statistician to study the effects of epoxy variability on circulator performance.

One survey of organizations that successfully implemented lean reveals that "strong leadership and commitment by top management" was "the reason for success" (Tonaszuck, 2000, p. 80). Leadership's active commitment to change is critical to overcoming the inertia associated with the status quo. Without this vocal and continued commitment, key personnel may (Senge et al., 1990, pp. 26-27):

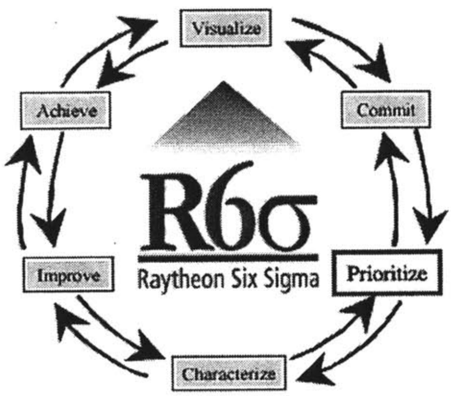
- Perceive that other time commitments will prevent them from implementing the change. Meeting existing obligations consumes most people's time and prevents them from accepting new work.
- Not ask for help or else be unaware that they need help. One key stakeholder remarked that pushing kits onto the production floor would be a suitable compromise between lean theory and the real-world necessity to produce finished goods. This person did not realize that he did not understand lean principles!
- Not think the change will improve the situation. Several key staff members believe that reducing lead time and WIP levels will not improve productivity. By contrast, they claim that high WIP levels improve productivity by ensuring that operators always have work to perform.
- Feel that senior management's actions are inconsistent with the proposed changes

By devoting time to the change effort and seeking the advice of experts, management sets an example for members of the team. Management must also encourage the team to develop a prioritized plan.

[5] Source: http://www.brainyquote.com/quotes/quotes/p/peterfdru121122.html accessed on March 14, 2004.

7. Step III - Prioritize

Not everything that can be counted counts, and not everything that counts can be counted.
- Albert Einstein[6]



Prioritizing tasks is the third step in the Raytheon Six Sigma™ process, because it helps ensure that committed resources are efficiently used. The prioritized tasks of this lean engagement are:

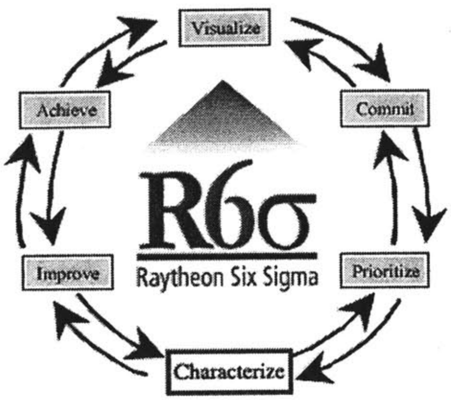
- Documenting needs and perceptions through interviewing stakeholders ranging from Directors to design engineers to hourly operators. The data from the interviews become some of the clues necessary to decipher the origins of the current production system.
- Understanding the current production system through measuring actual process times and creating value stream maps.
- Building awareness of lean principles and clarifying misconceptions through conversations, simple visual tools, and practice.
- Establishing institutional support for the change by enlisting the active support of the leaders of the Engineering and Operations organizations.
- Creating a circulator production system based on the value stream maps and the vision established by leadership.
- Creating visual controls and a tool for scheduling jobs to aid in the implementation of the circulator production system.

Armed with this basic plan, the team can now begin its analysis.

[6] Source: http://www.brainyquote.com/quotes/quotes/a/alberteins100201.html accessed on March 14, 2004.

8. Step IV – Characterize current production methods

Inside every small problem is a large problem struggling to get out.
– The Second Law of Blissful Ignorance[7]



Understanding the status quo, analyzing the problem, and articulating a solution is the fourth step in the Raytheon Six Sigma™ process. Observations of the production area and interviews with stakeholders not only provide an accurate description of current production methods but also provide clues that help uncover root causes for current production methods. Clearly, the future state should retain the positive parts while fixing the negative parts of the current state. Therefore, understanding both the technical and the organizational root causes of the current state is essential to proposing a viable future state.

This chapter contains the analysis of current production methods. Chapter 9 extends the root cause analysis to the broader organization. Finally, chapter 10 illustrates the proposal for the future state.

Analysis of current production methods

The Toyota Production System holds root cause analysis as a central tenet. Through the "five why" process, employees identify underlying problems and therefore prevent similar problems for recurring (Womack & Jones, 2003, p. 348). This thesis adopts that basic philosophy to uncover root causes for both positive and negative elements of current production methods.

Each of the following subsections isolates a characteristic of the status quo and attempts to uncover its root cause(s). After each root cause, we prescribe an action item, if required. The description of the future state in Chapter 10 incorporates all of these action items into one coherent system.

8.1 Consistently high quality products are produced

Root cause 1: Initial production methods focus mainly on quality and eliminating variability. Frequent operator reviews in the assembly process, a heavy reliance on automation, component screening on certain programs, and large lot sizes combine to minimize variability in the location of components as well as the thickness and location of epoxy. (Large lot

[7] Source: http://www.basicquotations.com/index.php?cid=221 accessed on March 14, 2004

	sizes minimize the number of setups and therefore minimize setup-induced variability.) As a result, an average of 95.4% of all circulators started on one high volume program pass final inspection. Customers rarely complain about quality problems.
Action item:	The production system should continue its focus on quality and use automation where required. Through a carefully designed and statistically based "design of experiment" or DOE, the team should study how variability in epoxy locations and thickness affect circulator performance. Where variability induced by setups is found to degrade performance, the team should study methods to further standardize setups. The final goal is a production process that is insensitive to setups and therefore amenable to economic order quantity-based lot sizes. Subsequent DOEs which study the effect of variability in circulator components on the performance of antenna arrays may be useful in eliminating the costly practice of component screening.
Root cause 2:	Engineering and operator pride drives the desire to ensure that customers remain satisfied.
Action item:	Retain pride in shipping quality products. Pride remains a core component of the future state.

8.2 Engineering staff continuously innovates new and high tech circulators

Root cause:	Because circulators manufactured at Raytheon have developed a reputation for being high performance, design engineers continue to receive requests for new types of circulators to meet challenging requirements. Design engineers have the desire and mandate to fulfill these requests. By controlling the circulator production schedule, design engineers can use the necessary resources (equipment and operators) to complete development work.
Action item:	The production schedule should allot a specific amount of time each period to accommodate engineering development work

8.3 Operators enjoy job satisfaction

Root cause 1:	Operators enjoy the flexibility of working in pairs or else alone
Action item:	Operators should retain some flexibility but should be responsible for completing jobs within a specified time
Root cause 2:	Operators enjoy process steps that involve machines more than they enjoy manual steps like cleaning and inspection
Action item:	By becoming responsible for starting and completing a job, all operators should perform a variety of tasks

8.4 Operators seek certifications to operate additional equipment

Root cause 1: Operators typically enjoy operating machines
Action item: Operators should be trained on all the operations required to start and finish a job.

Root cause 2: Operators' promotions are partly based on the number of certifications they receive
Action item: Operators should continue gaining certifications for machines they need to assemble and test circulators. By making operators responsible for completing jobs, operators will actually use their training.

8.5 Operators require continuous retraining on equipment

Root cause: Operators spend most of their time performing only a few tasks and therefore forget how to use other equipment
Action item: By accepting responsibility for starting and completing jobs, operators should perform a variety of tasks and therefore frequently use all necessary equipment

8.6 Lead times are long and not predictable

Root cause 1: Long queue times extend overall lead times. For example, for one high quantity program, queue times represent 80% of lead times and lead times vary as much as 600%.
Action item: By enforcing a first-in-first-out (FIFO) discipline and limiting WIP, the future system should limit queue times. While FIFO may appear to reduce flexibility, it actually helps make lead times more predictable. Jobs that require high priority can be prioritized in the launch plan. Short lead times will ensure that these "rush" jobs are started and completed quickly. Thus, FIFO can actually facilitate overall system flexibility.

Root cause 2: Jobs with "high priority" supercede jobs with lower priority.
Action item: The future system should incorporate a FIFO discipline to ensure that jobs are completed in the order they are started. Jobs with "high priority" should be placed in the same schedule as other jobs.

Root cause 3: Because of high circulator WIP levels, different jobs vie for the same resources. The result is long queue times (and therefore long lead times). Figure 4 below shows a typical amount of WIP during a busy period.

Figure 4: Circulator WIP

Action item: By controlling the amount of authorized WIP, the future system should limit queue times and therefore lead times.

Root cause 4: Because of high WIP levels, operators can switch between jobs when problems occur. The resulting lack of urgency to prevent problems (e.g. material shortages and machine failures) allows problems to recur. Unfortunately, bottleneck resources can sit idle for days because operators can perform other tasks. In short, by keeping everyone busy, the current production system creates the semblance of progress.

Action item: With limits on the amount of authorized WIP, production problems that stop work should become more visible. By attracting prompt attention to problems, the future system should ensure that problems are resolved and not deferred.

Root cause 5: The engineering culture at Raytheon emphasizes performance and not the value of time.

Action item: The importance of time should be stressed to all stakeholders. Operations personnel should perform all critical functions (like test) for all production-ready programs. Operations staff should therefore have control over maintaining this time-based production system

Root cause 6: Since the expected duration of each process is not understood, operators cannot evaluate their performance against a standard.

Action item: Value stream maps for each circulator family should contain cycle times for each process. Each job should carry a placard clearly delineating these expected cycle times. After these expected cycle times are established, the Operations Manager should check whether operators can consistently meet these expected cycle times. If they cannot, then the process itself may not be robust. Alternatively, the operators may require further training.

Root cause 7: Support staff is overworked, preventing them from promptly resolving production problems.

Action item: Management should prioritize the responsibilities of key staff members to ensure they have sufficient time to promptly resolve production problems.

The circulator manufacturing area is not the only manufacturer that suffers from long queue times! One study defines flow efficiency as the ratio of fabrication time to total lead time (Shields, 1996, p. 2). The report states that the flow efficiency for airframe manufacturers ranges from 0.02% - 0.8%, the flow efficiency for electronics manufacturers ranges from 0.02% - 18.7%, and the flow efficiency for engine manufacturers ranges from 0.7% - 13% (Shields, 1996, p. 64). The flow efficiency for one circulator program before the lean engagement was approximately 6%.

8.7 Queue times before test & test analysis dominate lead time

Figure 5 below shows the duration of each major step in the circulator assembly and test process for one type of circulator. The bar entitled 'target' shows the theoretical lead time for one lot, assuming that operators and equipment are available when needed. The bar entitled 'previous average' shows the average lead time over 16 lots prior to June 2003. Each major process step is delineated by a color. The height of each colored segment within each bar equals the average queue time plus the average cycle time for that process. When multiple processes are started and completed on a given day, only the last process appears on the chart.

'Lot 1,' marks the initiation of a pilot program to promote material flow by reducing queue times. Operators were shown how to process certain steps in parallel in order to reduce queue times. (For instance, while the first half of a lot was in one process, the second half of a lot was in the subsequent process) The results were dramatic for Lot 1-13, because operators completed more work each day than previously, as evidenced by the reduction in the number of colored segments within each bar. However, the pilot failed to reduce both the magnitude of and variability in the queue times before test.

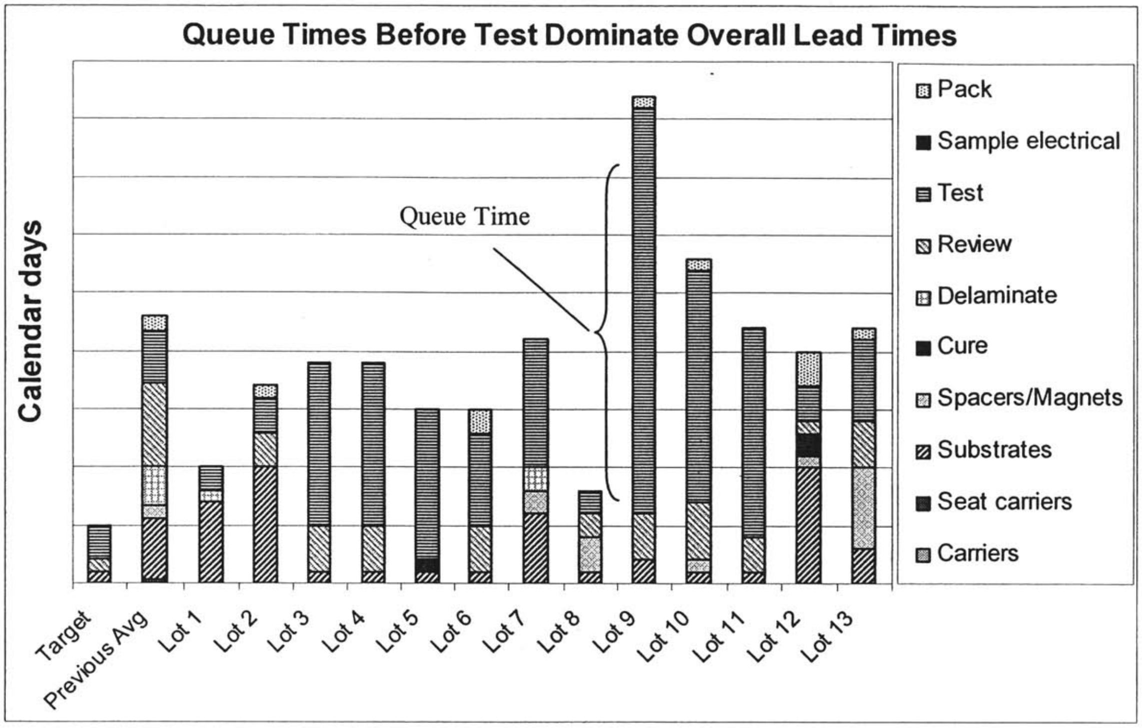


Figure 5: Queue times before test dominate overall lead times

Root cause 1: By controlling the test function, engineers retain control over which products ship to customers. Thus, they control the production system.

Action item: Test personnel from the Operations organization should be trained to perform the test function for all "production-ready" jobs, shifting control over test (and thus over system throughput) to the Operations organization.

Root cause 2: No accountability exists to complete jobs within a specified lead time

Action item: Each job should carry a placard clearly explaining the expected cycle time of each task.

8.8 High WIP levels often exist

Root cause 1: The presence of circulator WIP and component WIP is deemed acceptable. As a result of variability in lead times and fixed ordering costs, one stakeholder declared that "a stockpile of parts" is necessary. This general acceptance of WIP has caused the production area to house thousands of circulator components. For example, approximately $70,000 of magnets awaits use, as shown in Figure 6 below.

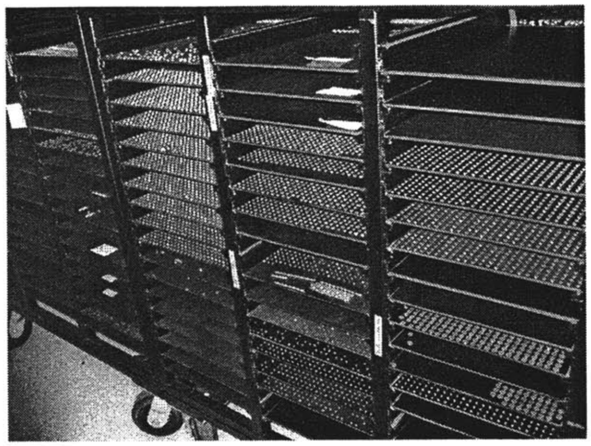


Figure 6: Magnet inventory

Action item:	By tracking inventory levels and using an updated kit release plan, the operations manager should order components in time for production. By using well established inventory models, the Operations Manager should set safety stock levels and reorder quantities that reflect the cost of component shortages and vendor lead times.
Root cause 2:	The desire to "level load" causes the staff to release kits into production even when a significant amount of WIP is already in production. One manager replied that releasing a kit gave operators "something to do."
Action item:	The future system should limit the amount of WIP authorized for production.
Root cause 3:	The staff wants to convince senior managers that all existing machines are being fully used. Stakeholders fear that senior managers will reject future capital requests if these managers see idle machines during unannounced visits. As a result, staff members want all machines to "keep moving."
Action item:	The team should ensure that all stakeholders (including senior managers) understand that the throughput of the bottleneck resource sets the upper bound for the throughput of the system. Maximizing the throughput of non-bottleneck resources needlessly generates WIP and diverts attention from the bottleneck resources
Root cause 4:	Since the circulator assembly process includes re-entrant flows, certain jobs must wait for resources
Action item:	Queue times caused by the reentrant flows should be carefully controlled by limiting WIP and enforcing a FIFO discipline.

8.9 Production area is often disorganized

While operators make earnest attempts to reduce the clutter within the production area, the lack of inventory control makes their jobs difficult. Figure 7 below shows the area used to store the shipping containers for circulators, known as waffle packs.

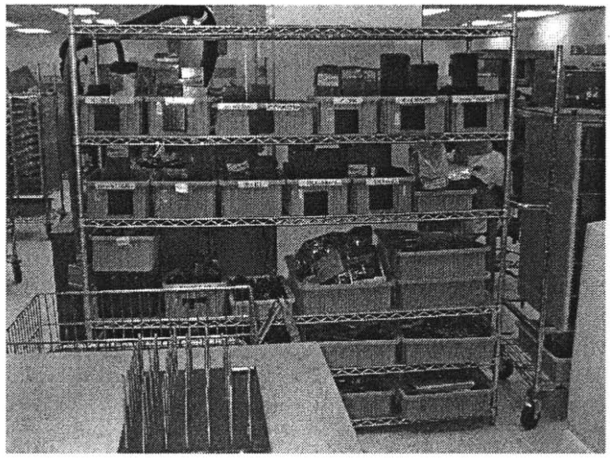


Figure 7: Waffle pack storage area

Root cause 1:	Production area is treated as an "engineering lab" therefore eliminating the perceived need to adopt production disciplines
Action item:	The Operations manager should possess the authority to impose the discipline required in a production setting

Root cause 2:	Because of high WIP levels, operators are sometimes unsure which jobs require their immediate intention
Action item:	The production system, loaded by a published kit release plan and operating under a FIFO philosophy, should ensure that operators understand which jobs require their attention.

8.10 Engineering jobs frequently receive more priority than production jobs

Root cause:	Engineering stakeholders seem to prefer spending time on engineering jobs. One possible explanation is that validating designs is more intellectually stimulating process than processing routine jobs.
Action item:	All jobs should be processed on a first-in-first-out basis

8.11 The link between WIP and lead time

Long lead times and high WIP levels are related. When a production system has constrained capacity, an increase in WIP levels increases queue times. Increased queue times in turn increases lead times. When people begin to mentally accept long lead times, they lose the feeling of urgency to complete jobs. Job completion rates therefore fall, leading to even higher WIP levels. The causal-loop diagram shown in Figure 8 shows this vicious cycle denoted by the "+" sign in the counterclockwise loop. WIP will continue to grow until people's value for time increases, people understand expected durations, and FIFO discipline is enforced. The diagram also explores the effects of other variables like re-entrant processes, accountability, and disorganization on WIP and lead time. Arrows with positive signs indicate that an increase in the preceding variable causes an increase in the subsequent variable, and vice versa.

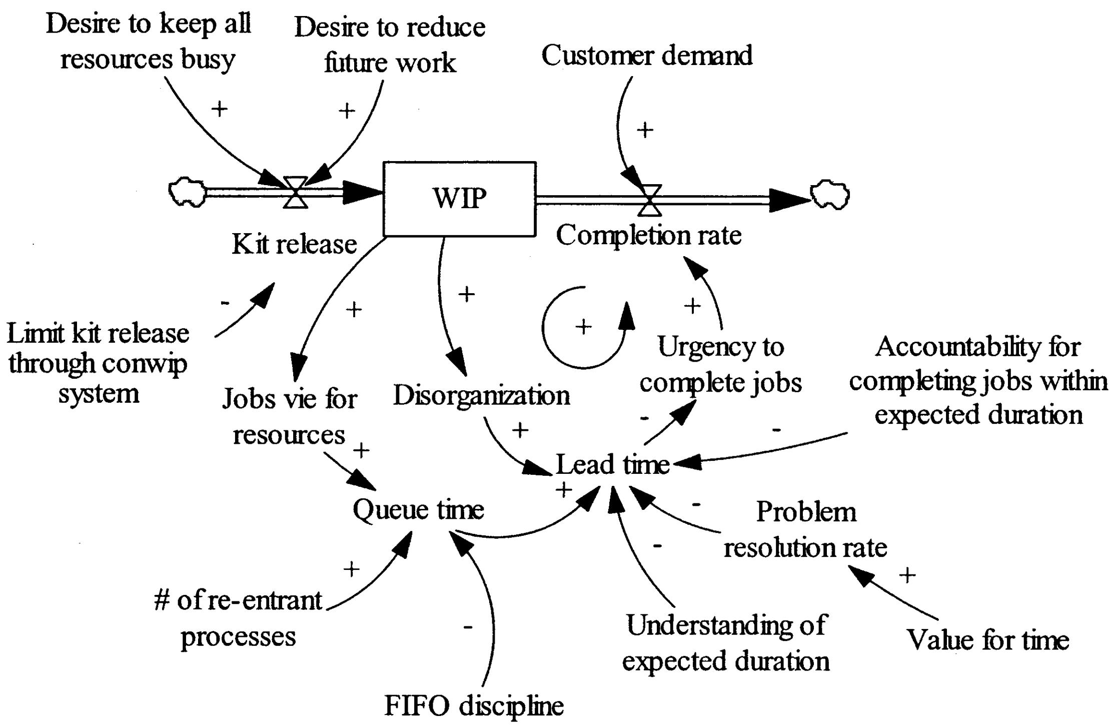


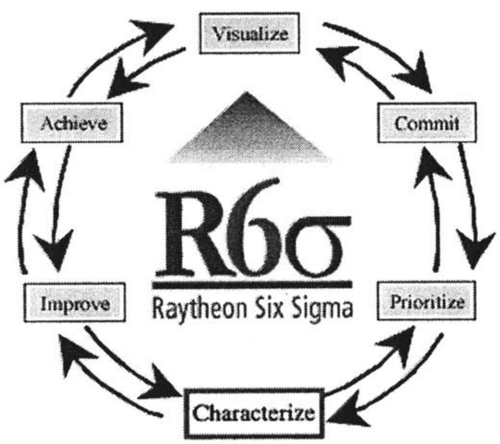
Figure 8: WIP and lead time causal loop diagram

By providing insights into how people's behaviors affect lead time and WIP, Figure 8 reveals the changes necessary for the new system to successfully lower both WIP levels and lead times. For example, by increasing the FIFO discipline, we reduce queue times. A reduction in queue times reduces expected lead times. When jobs are quoted to customers with shorter lead times, production staff naturally feels greater urgency to complete jobs. Job completion rates will increase as a result, leading to a reduction in WIP.

While the majority of the root causes discussed have technical solutions, some reveal deeper organizational implications. For example, engineering pride in the product's technical excellence is evidence that the broader organization values performance; solutions which are perceived to jeopardize performance will be universally rejected. The tendency for operators to answer the phone using the words "engineering lab," is an indication of the ingrained culture. Therefore, understanding the organization is critical to implementing change. It is not novel to claim that the root causes for successes and failures lay within the organization. In fact, the report published by the space shuttle Columbia's accident investigation board concludes:

> When causal chains are limited to technical flaws and individual failures, the ensuing responses aimed at preventing a similar event in the future are equally limited...Such corrections lead to a misguided and potentially disastrous belief that the underlying problem has been solved" (Gehman et al, 2003, p.177).

9. Step IV – Characterize organization using the Three Lens Model



The Three Lens Model is useful in understanding the current organization's behavior and in creating an effective strategy for change management (Ancona et al, 1999). The model's creators submit that different forces drive people's behavior. These forces are most clearly seen using the strategic design lens, cultural lens, and political lens. The model's basic premise is that "...an analysis that considers and combines all three lenses is more likely to reveal the complex interdependencies of the organization, the difficulties of implementing change, and the heterogeneity among individuals and groups" (Carroll, 2001, p. 10)

9.1 Strategic design lens

The strategic design lens uses a logical approach to understanding organizations. It assumes that individuals are rational and that organizations can be structured to achieve a goal. Using this lens, we study how people are grouped together to accomplish related tasks, how these groups are linked through both formal mechanisms (e.g. liaison and cross-functional teams) and informal mechanisms (e.g. networks of personal relationships), and finally how people's efforts are aligned with the goals of an organization through performance-based rewards and peer recognition.

9.1.1 Grouping and linking

The Engineering and Operations organizations report to separate vice presidents within Space and Airborne Systems. The Engineering organization has been designed with the explicit intent of inventing new products to meet current and future needs. In this matrix organization, highly talented engineers are grouped by specialty and then assigned by their line managers to specific programs. Some senior engineers who are also program-oriented lead research activities consistent with the strategic business needs identified in Raytheon's technology roadmaps.

Meanwhile, the charter of the Operations organization is providing customers with products that fulfill the technical, cost, quality, and schedule requirements. The vice president of Operations for Space and Airborne Systems stated, "We win business through technological excellence...we keep business through operational excellence." (on 12/9/03) Clearly, Raytheon seeks to develop its Operations organization into another source of competitive advantage.

The third major functional group within SAS is program management. Often staffed by the Engineering Organization, program management serves as the customer interface. Program managers are therefore often technical people with interests in management.

Solid State Microwave (SSM) is the specific organization within SAS that produces substrates, circulators, and microwave integrated circuits (MICs). At present, SSM is grouped by function as well as by product and process. Two examples of functional groups are the process engineering group and operator staff. On a given program, process engineers will make designs more producible, program equipment, train operators, aid the transition to manufacturing, and support continuous improvement. Meanwhile, operators will perform the actual value-added assembly functions for products. Thus different functional groups are linked together to form a broad team for each program.

Since the majority of operators within SSM build MICs, MICs gain much of SSM management's attention. Thus, a supervisor exists for each group of 10-15 MIC operators who perform similar functions. However, since the circulator organization is small, no formal reporting structure within the circulator organization exists. Thus, operators report administratively to a MIC supervisors even though MIC supervisors have little expertise in circulators. The circulators receive daily work instructions from the engineering and process engineering staff. While this dual structure is a natural result of the circulator organization's small size, it unfortunately does not always ensure that operators' concerns are adequately resolved. For example, one operator voiced her frustration that she could not rely upon management to aid in her professional development. She felt that no one had her interests at heart.

9.1.2 Metrics and Incentives

Raytheon recognizes that metrics and incentives align people's interests to overall business goals. An internal Raytheon website states, "The Performance Development process guides the alignment of goals throughout the organization, and facilitates the achievement of meaningful objectives...." Business leaders "ensure they are setting program, department, team, and individual objectives that align with and contribute towards the achievement of corporate and business goals.[8]" Once department goals are established, line managers and their employees together identify goals (or metrics) against which employees are measured. Managers and employees then meet periodically

[8] source: http://home.ray.com/desktophr/perform/ accessed on March 01, 2004.

to assess personal contributions and identify areas for improvement. Employees are typically rewarded for their performance by:

- Merit raises
- Monetary achievement awards for major accomplishments
- Profit sharing if the business meets its goals
- Spot awards for meeting customer commitments or increasing customer satisfaction.

Senior employees are also eligible for the "Results Based Initiative," in which they are monetarily rewarded for documented personal contributions that helped the business meet its goals.

Within the Solid State Microwave organization specifically, some groups enjoy the benefits of strong links between goals, metrics, and incentives, while other groups must improve these links. Process engineers, for instance, enjoy a strong link between goals and metrics. Improving process robustness is a high level department goal, and process engineers are measured by their ability to improve yields and reduce lead times. While financial incentives exist to reward contributions, non-financial incentives exist as well. For example, peer pressure to publish noteworthy accomplishments in a monthly newsletter encourages process engineers to remain productive.

Managers of operators review the performance of individual operators against department goals. Since management's focus traditionally centers on MICs, established metrics for RF performance and quality standards exist for MICs. Through consistently producing quality work and participating in dedicated training, operators can also gain the title of Certified Operator. Certified Operators can inspect their own work. Managers also use additional incentives like merit awards, individual and team "spot light on performance" awards, and commendations during all-hands meetings to reward exceptional contributions. Many operators actively pursue training on different machines because certifications on multiple processes are needed for promotions. In short, the link between performance and rewards is fairly transparent for MIC operators.

By contrast, the link between performance and rewards is more subjective for circulator operators. Without quantifiable metrics (like lead time or first pass quality) to continuously gauge their performance, circulator operators do not benefit from immediate feedback. While managers can reward operators with merit awards, their inability to tie an award to a visible metric diminishes the award's long term value. Without data, managers are also forced to base promotions on seniority, certifications on machines, reputation, and qualitative assessments.

When designing incentives to link groups, managers face a difficult problem. While managers can quantify some of the factors that will improve the business' performance, managers must be cautious in creating incentives. For example, cross-trained employees generally increase the flexibility of a workforce, allowing managers to deploy operators in response to shifts in the bottleneck. By alleviating bottlenecks, managers can increase throughput and therefore revenue. In an attempt to encourage cross training, management has generally rewarded operators who gain certifications on multiple processes with promotions. In response, *operators actively seek certifications, even if they know they will not use them*. While management is correct in rewarding operators who gain additional certifications, it must also actively promote a program to ensure that operators use their newly-gained knowledge. Otherwise, operators will continue to require "re-training," as in the circulator area.

This strategic design lens is useful in understanding the dynamics behind people's behavior. By understanding how people are grouped, linked, and aligned, we begin to understand some of the root causes of their actions. However, the strategic design lens alone does not yield a complete definition of an organization. If this lens alone were sufficient, managers could easily design an organization to achieve a goal. The traditional importance given to explicit organizational design causes some businesses to "have the notion that if all the boxes on organizational charts could be properly arranged and described, the business could run itself" (Hyland, 1994, p. 259). To the chagrin of many managers however, leading an organization does not end with creating an organization chart and an incentive system.

9.2 Cultural lens

Seasoned academics and managers attribute much of an organization's success or failure to its culture. Literature is replete with ex-post analyses of how a company's culture either propelled it to success or doomed it to failure. Two quotes which succinctly describe the essence of culture are:

- "Organizational culture refers to the values, norms, beliefs, and practices that govern how an institution functions. At the most basic level, organizational culture defines the assumptions that employees make as they carry out their work. It is a powerful force that can persist through reorganizations and the reassignment of key personnel" (Gehman et al, 2003, p. 177).
- "Culture is a way of life; it is what we do around here and why we do it" (Carroll, 2001, p. 8).

Raytheon's employees deserve to take pride in their accomplishments. Employees carefully guard the source of their company's competitive advantage: the technical excellence of their products. Change agents must therefore convince stakeholders that initiatives will fix problems without jeopardizing existing successes. The key to successful change management is therefore ensuring that stakeholders do not view the change as an attack on the company's culture. The vice president of SAS Operations declared that the challenge of change management is "all culture."

Much of SSM's culture was defined before Raytheon acquired the business unit from Hughes Aircraft. Hughes' culture stressed the importance of technical performance, even at the cost of lowering the importance of manufacturability and standardization. When evaluating Hughes' needs after his appointment as general manager, Lawrence Hyland stated, "It was obvious a research and development organization with talents for innovation would be required" (Hyland, 1994, p. 248). Hyland proceeded to craft a premier research and development organization. A natural result was that there "might be only one individual in the entire company capable of completing a particular element, because the requirements might demand an educated, natural problem-solving instinct rarely available...Each division and its components ultimately had a general organizational structure, built around the individual. There could be no standard approach, applicable throughout the company, for tackling various jobs." (Hyland, 1994, p. 265) Raytheon is not alone in focusing on performance. Charles Fine, professor of Management Science at the MIT Sloan School of Business, states:

> "In industries such as consumer electronics and automobiles, where innovation is the watchword, product designers sat in their labs at the top of the hierarchy, developing marvels of technology. They left it to the drudges in manufacturing to figure out how to churn out their inventions in high volumes at costs that would make the manufacturing venture feasible...The research laboratory, for instance, was certain to have the highest walls, and only the initiated might enter its sacred chambers. Having invented a new product, these architects of the imagination would toss their designs over the walls of the lab and down to the people in manufacturing, who might well have to guess what the design was for – and then how to make it" (Fine, 1998, p. 129).

As a result of its design and analysis-centric culture, the value in industrial engineering was not communicated. In fact, while scientists and design engineers were given the prestigious title of "Member of Technical Staff," degreed industrial engineers were given a title that did not command the same respect. Some in the organization viewed industrial engineers as high level technicians. This perception has, however, changed over time as the operations organization has grown in strength.

One framework that describes the evolution of manufacturing organizations has four stages and is especially relevant to the long-run strategic direction for SAS (Wheelwright & Hayes, 1985, pp. 99-109):

- Stage one organizations view their manufacturing organization as an "internally neutral," "low-tech operation that can be staffed with low-skilled workers and managers...The aim is not to maximize [manufacturing's] competitive value but to guard against competitively damaging problems." Stage 1 organizations include "sophisticated high-technology companies, which regard *product technology* as the key to competitive success and *process technology* as, at best, neutral."
- Stage two organizations view their manufacturing organization as "externally neutral" by seeking "parity with major competitors." They follow industry practices, view capital investments as a means to achieve temporary competitive advantages, and regard economies of scale as the key to efficiency.
- Stage three organizations view their manufacturing organization as "internally supportive" and "expect manufacturing to support and strengthen the company's competitive position." An explicit manufacturing mission statement and strategy helps achieve long term goals.

- Stage four organizations view their manufacturing organization as "externally supportive" through its contributions to the overall "competitive success." As a "source of strength by itself," manufacturing is a "valued source of general management talent for the entire organization."

While the SAS Operations organization contains some of the positive elements of stages three and four, it is currently at stage two. Raytheon, however, is clearly striving to attain stage three and ultimately stage four through:

- Selecting a Chief Executive Officer who previously worked in the Operations organization
- Placing the office of the Vice President of Operations adjacent to the office of the President
- Embarking on lean initiatives
- Institutionalizing six sigma improvement processes

SAS Operations has already made tangible progress towards attaining stage three: through increasing operational efficiency, it has saved several million dollars over the past few years and has pledged to save more money in the years ahead.

Even though Operations has grown in its technical excellence, perceptions and culture are slower to change. The success of this change initiative is contingent upon building credibility. Since the Engineering organization currently manages the circulator facility, Operations staff at all levels must be knowledgeable and confident about lean manufacturing principles.

Unfortunately, prior experiences with Operations personnel did not always instill confidence within the Engineering organization. For example, glitches within the MRP implementation reflect badly on the Operations organization. Because of data entry errors governing lot sizes and the perceived inability to easily and reliably fix these errors, engineers are skeptical of all MRP data. One engineer joked that even operations staff are forced to manipulate the system to avoid problems. Attitudes like these indicate that Operations must continue building credibility with Engineering.

Because of its performance-oriented culture, SAS employees will tend to reject initiatives that compromise performance. Some design engineers unfortunately view lean manufacturing as a threat to performance. Since lean explicitly stresses the importance of time, some feel that lean does not value performance. In fact, one stakeholder declared, "lean doesn't apply here!"

Proponents of lean must therefore stress the compatibility of lean and a performance-based culture. For example, cycle time consistency is directly proportional to process robustness, since processes with consistent cycle times are most likely stable. Stable processes likely result in few defects and therefore high quality. By contrast, inconsistent cycle times may either result from unresolved problems within a process or else a lack of process standardization. Both of these root causes lead to waste. In short, cycle time consistency is an indicator of process health. Healthy processes result in consistent quality.

9.3 Political lens

While the strategic lens helps us understand how we can use explicit organizational tools to achieve business goals, the cultural lens helps us understand how people's beliefs will affect their acceptance of a change initiative. The third lens, the political lens, helps us understand the dynamics of power within the organization. More specifically, the lens reveals the sources of power within the organization and helps us examine how stakeholders with different interests vie for power (Carroll, 2001, p. 5). Clearly, this tool helps us modify and then frame a change initiative to appear less threatening to those with power. We can also induce the cooperation of certain people by providing them with the access to power.

Social scientists have extensively studied the sources of power within an organization. Some common sources of power are: (Carroll, 2001, p. 6)

- Formal position
- Access to scarce resources
- Formal rules
- Information or expertise
- Persuasive abilities
- Charisma

While the strategic design lens shows that people with common skills or functions often coalesce into groups, the political lens reveals that people also form coalitions when they share common interests. Indeed, certain stakeholders ranging from operators, process engineers, and design engineers united to support the lean initiative. Others from all three groups also united to challenge the initiative. This latter group may have perceived the lean initiative as a threat to their power. States John Carroll, professor of Behavioral and Policy Sciences at the MIT Sloan School of Management, "major changes in mission, strategy, organization, or personnel are not simply rational moves to accomplish organizational goals, but also threats to those who hold power and opportunities for those who want more power" (Carroll, 2001, p. 7).

Power is therefore a dynamic force. It can shift because of factors external and internal to the organization. Convinced of the benefits to lean, some Raytheon customers like the Boeing Company actually want Raytheon to define how it will use lean initiatives to improve metrics like lead time and quality. Because of its interface with customers, program management also holds significant power within SAS. A change initiative supported by program management can gain significant momentum; a change initiative without support may languish.

Other lean initiatives are borne because internal management faces a problem and has turned to lean as a solution. Vocal commitment from both Engineering and Operations directors to this circulator lean initiative clearly forces some members of anti-lean coalition to reconsider the lean proposal. More broadly, the Operations organization must gain more power in the design process to ensure that it can deliver future products to customers on cost and on schedule.

Power in the Circulator Organization

Queue times before test drive the magnitude and variability within circulator lead times. At present, engineering personnel are required to process the test data because neither operators nor Operations staff possesses the knowledge to interpret test data. Already overloaded by other commitments, engineers are unable to promptly analyze test data. Thus, while one lot of circulators waits for data analysis, another lot of circulators wait in queue before test. Thus, engineers control the flow of circulators because they control the test process. Engineers can also expedite certain programs by changing the priority of programs during test. The aphorism "Power is the ability to get things done" (Carroll, 2001, p. 6) holds true in circulator production.

Ironically, in most cases, the test computer actually autonomously performs the pass/fail decision for each circulator. An engineer must merely open the correct file, understand the data's format, and then remove circulators which do not pass test. Since testing MICs is typically deemed a more complicated task than assembling MICs, few in SSM have challenged the assumption that Engineering personnel must interpret test data. Fortunately, the Operations organization is now challenging this and other assumptions.

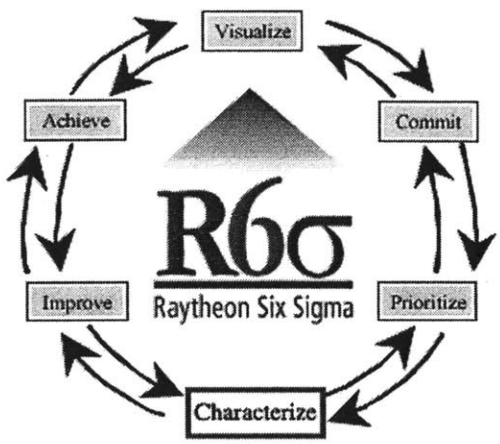
9.4 Concluding remarks on organizational analysis

Describing an organization is relatively easy. Explaining the behavior of an organization, however, is far more difficult. Emotions and pride affect our actions and therefore complicate the analysis of people's behavior. After completing our analyses, we must communicate our findings. This process is perhaps the most difficult, again because of emotions and pride. We must therefore speak carefully and rely upon the professionalism of our colleagues. Fortunately, everyone in the circulator organization has the same high level objective: to help Raytheon deliver the best possible products to its customers.

This root cause analysis of technical and organizational issues will require refinement over time. As we characterize the future state and begin implementation, we will test our root causes hypotheses. Any errors we made will surface in due time!

In the next section, we proceed with our definition of the future state.

10. Step IV – Characterize the future state



The goal for the circulator production area is simple: attain the vision communicated by the Directors of Engineering and Operations. As described earlier, the vision has five objectives for circulator production. Our recommendation for the future state contains specific elements that target components of the vision statement, as listed in Table 1:

Future state	Relevant component of vision statement
Delineated roles & responsibilities	Predictable production system
Constant wip or "conwip" system	Predictable production system
Inventory policy	• Predictable production system • Value stream integration
Lot sizing policy	• Predictable production system • Resource optimization
Scheduling and quality tools	Scheduling and quality tools
Metrics	Resource optimization

Table 1: Relationship between future state and vision

The remaining sections of this chapter detail each component of the future state. Together, these components form an overall plan for achieving the circulator vision.

10.1 Delineated roles & responsibilities

The success of a time-based production system is contingent upon clearly defined roles and responsibilities for stakeholders. Important functions like preventative maintenance, process improvement, and inventory replenishment will only occur if the organization assigns these functions to individuals. If people do not reliably perform these tasks, the system will falter, and people will resort to their familiar roles as "fire-fighters." When the inevitable production problems occur, operators must know whom to call. Support staff will only respond quickly if management establishes that expectation.

The Directors of the Engineering and Operations organization have delineated specific roles for their respective organizations and have conveyed these roles to all circulator stakeholders. While they divided responsibilities, the Directors emphasized that continued cooperation across both organizations is vital. Stated responsibilities cannot be all-encompassing, as undefined needs will emerge, and responsibilities will evolve.

Table 2 below details some of the key responsibilities for each group (Chatterson & Wallace, 2003, p. 4):

Engineering staff	Operations staff
Provide technical support	Maintain and provide resources for all programs
Innovate new circulators	Allocate resources for engineering development
Conduct design reviews for new circulators	Meet production schedules
Estimate and approve budgets for development programs	Estimate and approve budgets for production programs
Enter engineering programs into capacity model	Maintain capacity model[9]
Help create design guide for new circulators	Help create design guide for new circulators

Table 2: Roles and responsibilities

By defining specific roles and responsibilities, management is creating accountability for actions and beginning the power transfer and sharing process. For example, by transferring the test and data analysis functions for specific programs to Operations personnel, the Engineering organization is essentially sharing its control over the production system. By emphasizing that design engineers now have more time to perform intellectually challenging design work, management is attempting to mitigate resistance and accelerate the transition.

10.2 Conwip System

Technically, the circulator production system is based on a "constant wip," or conwip, system. By limiting WIP and employing a FIFO method, a conwip system reduces the queue time for jobs thus reducing lead times. Production problems, caused by machine failures or rework, result in a visible stoppage of progress; operators cannot just switch to working on other jobs. When problems become more visible, they demand quicker resolution. The combination of reduced queue times and higher visibility with production problems combine to make lead times more predictable.

10.2.1 WIP levels

Little's Law clearly summarizes the relationship between WIP, lead time, and throughput (Hopp & Spearman, 2000, p. 223). It states:

$$WIP = throughput \times lead\_time$$

Equation 3: Little's law

[9] As part of this lean initiative, we created a simple but useful capacity model. Appendix 1 includes the equations behind the capacity model and a summary chart.

Assuming that sufficient capacity exists for throughput to match demand, the amount of WIP authorized for production is directly proportional to customer demand; if demand increases and lead times remain constant, the system must process more WIP simultaneously.

Additional WIP may be required to prevent the bottleneck from starving. Since the throughput of the bottleneck resource sets the upper bound of the system's throughput, starving the bottleneck can reduce the system's throughput. The Theory of Constraints therefore advocates placing additional WIP upstream of the bottleneck as insurance against upstream production problems that may starve the bottleneck. While this additional WIP will result in longer lead times, this additional WIP maximizes the chance that the bottleneck will continue producing. Clearly, increasing process robustness will not only improve quality but also reduce the need to hold this additional WIP.

10.2.2 Conwip illustration

Figure 9 below illustrates how the circulator production system uses the conwip principle.

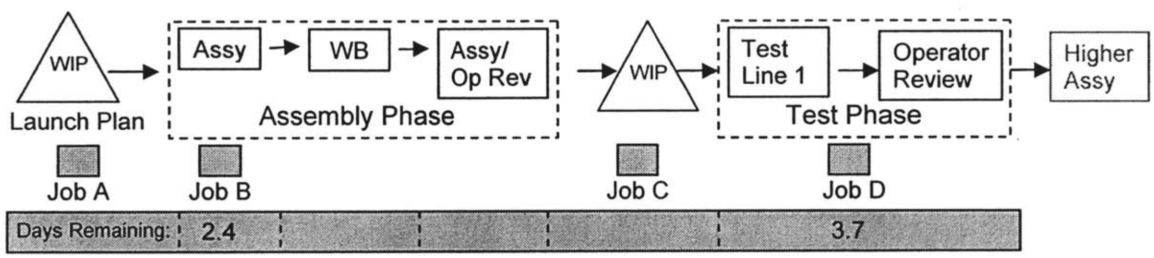


Figure 9: Circulator conwip system

Since circulator production involves re-entrant flows within the assembly phase, the entire production process is divided into kitting, assembly, and test phases. WIP is essentially pushed within each phase but pulled between phases. Circulators never re-enter the kitting phase after entering the assembly phase, and circulators never re-enter the assembly phase after entering the test phase. Thus, once operators pull a job into a phase 'n+1', they can pull another authorized job into phase 'n'.

By limiting the number of available conwip cards (shown by the colored boxes in Figure 9) and pulling jobs between phases, the system prevents the uncontrolled buildup of WIP within a phase. Based on a hypothetical demand and the need to minimize the chances of starving the bottleneck test machine, four lots are authorized for production in the Figure 9 above. Typically, two lots will be in assembly, one lot will wait in WIP before test, and one lot will be in test.

The assembly phase contains three generic sub-phases: pre-wirebond assembly, wirebond, post-wirebond assembly. Since outside personnel perform wirebonding, denoted as WB in Figure 9, circulator operators can process one job while outside personnel process the wirebond job. Therefore, different lots can occupy two of these three sub-phases. The number of lots within each phase will vary over time because cycle times for each process vary between jobs.

10.2.3 Cycle time consistency

After grouping circulators into families and documenting cycle times in value stream maps, we establish the expected cycle time durations for each process for each circulator family. By establishing a standard, we expect to reduce cycle time variability. With reduced variability, we can minimize the probability that the bottleneck will starve. In short, consistent cycle times facilitate bottleneck management and help ensure a predictable throughput.

Since operators can perform certain machine-intensive activities concurrently, we can divide a lot into two smaller lots. As a result, queue times, and therefore lead times, reduce. A hypothetical "structured flow" which visually depicts the subdivided lots' progression through the assembly process is shown in Figure 10. In reality, a job will wait in queue before test until the prior job completes test. This queue time is not shown in Figure 10.

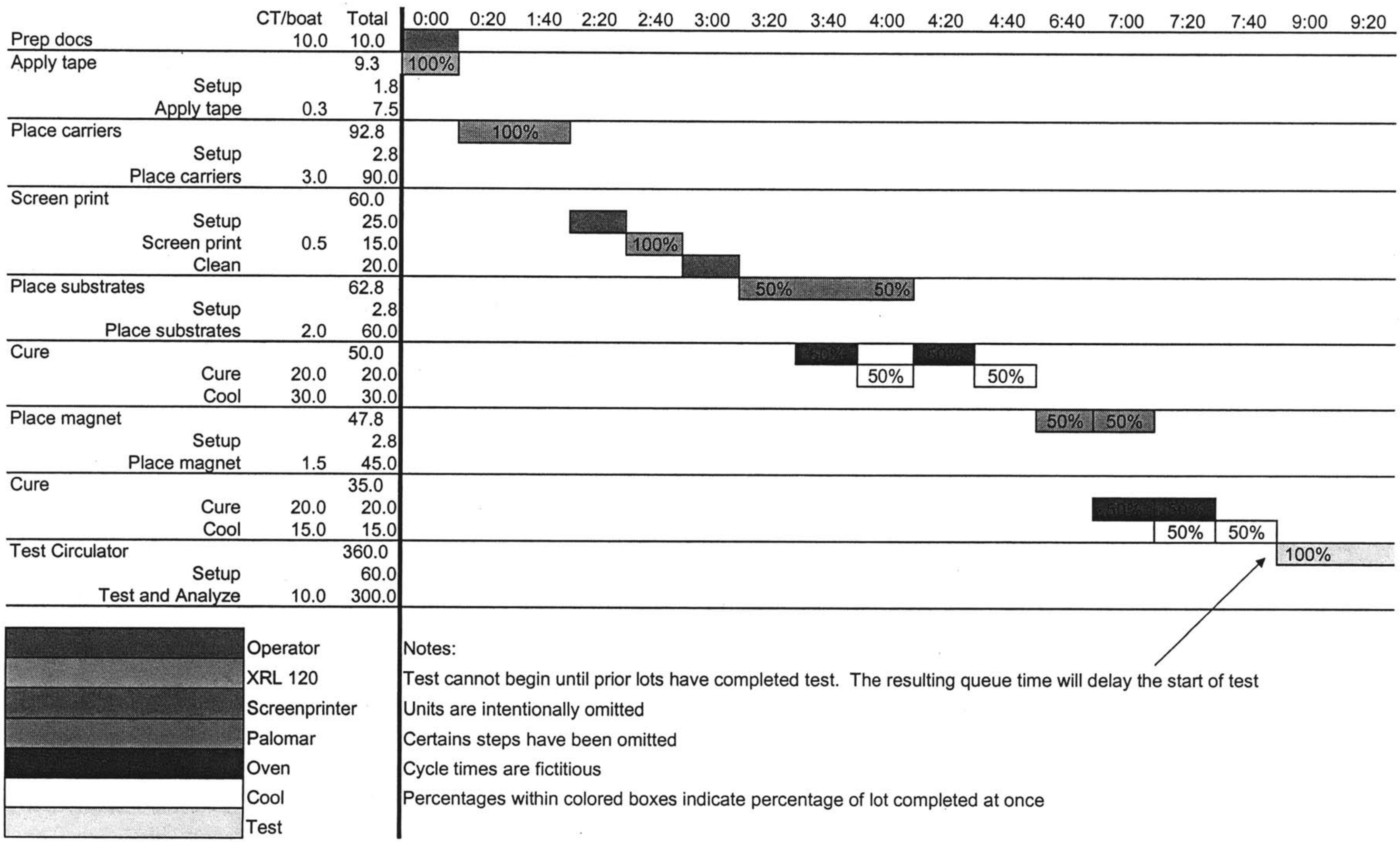


Figure 10: Hypothetical structured flow

10.3 Inventory policy

Do not worry about your difficulties in mathematics. I can assure you mine are still greater. – Albert Einstein[10]

The Operations manager can choose from a variety of inventory models to optimize inventory levels. The Continuous Review Model and the Silver Meal Heuristic are two of the more appropriate models. While the first model is simpler to understand, the second model is more powerful and will result in a more optimal solution.

10.3.1 Continuous Review Model

In the Continuous Review Model (Simchi-Levi, Kaminsky, Simchi-Levi, 2003, pp. 62-63), we calculate an "economic order quantity" or EOQ to balance fixed ordering costs and holding costs per period. For each product, *i*, we define the following variables:

$K(i)$	= fixed order cost
$\mu_{demand}(i)$	= average demand per period
$\mu_{lead\_time}(i)$	= average lead time per period
r	= carrying charge (assumed constant for all inventory)
$\sigma^2_{demand}(i)$	= variance in demand per period
$\sigma^2_{lead\_time}(i)$	= variance in lead time per period
$v(i)$	= unit cost

Equation 4 below gives the EOQ (Roemer, 2002, pp. 21-26) and is derived in Appendix 2:

$$EOQ(i) = \sqrt{\frac{2 \times K(i) \times \mu_{demand}(i)}{v(i) \times r}}$$

Equation 4: Inventory replenishment economic order quantity

Fixed order costs are any costs imposed by the vendor or the Procurement organization for each order placed. Carrying charges typically reflect the cost of capital, insurance costs, and storage costs per period. Carrying charges typically range from 15% to 20% per year.

This model also incorporates a reorder point to trigger a new order, using Equation 5 below (Simchi-Levi, Kaminsky, Simchi-Levi, 2003, p. 62).

$$\text{Re}order\_po\text{int}(i) = \mu_{demand}(i) \times \mu_{lead\_time}(i) + safety\_stock(i)$$

Equation 5: Reorder point

[10] (Edited by Calaprice, Alice, The Quotable Einstein, Princeton: Princeton University Press, 1996, p. 177)

Finally, this model includes a safety stock to help prevent a material shortage during the reorder period. We calculate safety stock using Equation 6 below (Simchi-Levi, Kaminsky, Simchi-Levi, 2003, p. 62).

$$safety\_stock(i) = z(i)\sqrt{\mu_{lead\_time}(i) \times \sigma^2_{demand}(i) + \mu^2_{demand}(i) \times \sigma^2_{lead\_time}(i)}$$

Equation 6: Safety stock

The variable *z(i)* reflects the cost of a shortage and assumes that lead times and demand are normally distributed. If enough components must be available during 95% of the reorder periods (corresponding to a 95% service level), *z* equals 1.65. If we require a 99% service level, *z* equals 3.08. Clearly, higher service levels are more conservative but also lead to higher inventory carrying costs. The terms within the square root reflects the fact that variability within demand and variability within lead time both increase the risk of shortage. In short, safety stock increases with increased conservatism, lead times, variability in lead times, demand, and variability in demand. In our case, circulator demand is well known in advance. Variability in demand is therefore negligible.

10.3.2 Silver-Meal Heuristic

While the Continuous Review Model allows demand to vary, it assumes that the average demand is stationary, or does not vary with time. Since circulator demand is growing rapidly, using the Continuous Review Model will lead to higher than optimal inventory levels (and therefore higher carrying costs) if the time horizon is long, and higher than optimal ordering costs if the time horizon is short. Several alternatives to the Continuous Review Model exist. One heuristic that is more powerful and will yield better results is the Silver-Meal Heuristic, which is named after its creators (Silver, Pyke, Peterson, 1998, pp. 210-213). This heuristic allows average demand to vary with time.

The Silver-Meal Heuristic attempts to minimize the total relevant costs per unit time. Key assumptions are:

- Future demand is known
- Demand can vary with time. (In the equations below, $D_t(i)$ represents the demand for product *i* in period *t*.)
- Inventory replenishment arrives at the beginning of a period and suffices for the next *T* periods. The next scheduled replenishment arrives at the end of *T* periods.

Since average demand may vary with time, the replenishment quantity and reorder frequency may vary as well. The heuristic helps us determine a new *T* and appropriate order quantity for each reorder cycle.

The replenishment quantity, *Q(i)*, for each product for the next *T* periods equals:

$$Q(i) = \sum_{t=1}^{T} D(i,t)$$

Equation 7: Silver-Meal replenishment quantity

Total relevant costs per unit time, *TRCUT(T)*, equals:

$$TRCUT_i(T) = \frac{K(i) + Carrying\_\cos ts(i)}{T}$$

Equation 8: Total relevant costs per unit time

$$Carrying\_\cos ts(i) = v(i) \times r \times \sum_{t=1}^{T} (t-1) \times D(i,t)$$

Equation 9: Silver-Meal carrying costs

The quantity *(t-1)* appears in the carrying costs equation because inventory held for *t* periods incurs carrying costs for the *(t-1)* periods prior to its use. Parts used in period *t* do not incur carrying costs for period *t*.

With this heuristic, we evaluate $TRCUT_i(T)$ for increasing values of *T*. We find the optimal value for *T* when $TRCUT_i(T+1) > TRCUT_i(T)$.

Replenishment of the component inventory must occur in time for the next production period. This replenishment order must be placed at T_{order}, which equals:

$$T_{order}(i) = T(i) - \left(\mu_{lead\_time}(i) - z(i) \times \sigma_{lead\_time}(i)\right)$$

Equation 10: Time for replenishment order

At the conclusion of one period, we repeat the entire process above to determine the new *T* and *Q(i)* for the next period.

10.4 Lot sizing

Setups not only cost money but also erode capacity. Traditional batch and queue production therefore promotes the amortization of setup costs over a large manufacturing quantity, thereby reducing the average setup cost per part. Since the setup plus teardown time associated with one circulator epoxy process is 45 to 90 times longer than the process cycle time, circulator staff found large lot sizes as the solution to their problem.

By contrast, lean manufacturing responds to large setup costs by lowering them! Lean explicitly supports the identification and elimination of the root causes of large setup costs. For example, Taiichi Ohno, father of the Toyota Production System, realized that Toyota could not afford to buy a dedicated sheet metal press for each body panel. It also could not afford to wait one day for specialists to change presses. Therefore, he purchased American presses in the late 1940s and experimented with different techniques to quickly change over dies. After several years, he succeeded in reducing the changeover time from one day to three minutes and eliminated the need to hire dedicated specialists (Womack, Jones, & Roos, 1990, pp. 52-53).

Despite lean's emphasis on continuous improvement, setup costs will likely not disappear. Unfortunately, setups will therefore continue to erode capacity. If demand exceeds production capability, eroded capacity directly reduces throughput and therefore reduces revenue. The intelligent use of lot sizing techniques can accommodate these nonzero setup times while minimizing lot sizes. Smaller lot sizes have the following benefits:

- Smaller lot sizes shorten queue times and therefore enable shorter lead times.
- Smaller lot sizes limit the exposure to defective WIP, because downstream processes may detect quality problems that stem from errant upstream processes. Smaller lot sizes therefore reduce the potential for rework.

Previously, circulator lot sizes stemmed from the need to amortize setups and the need to control variability in epoxy application. Because of very tight tolerances on the position and thickness of epoxy, even subtle changes in a specific epoxy machine's setup could lead to unacceptable variation. While process engineers have standardized the setups, small differences remain across setups. As a result, some customers contractually stipulate that all circulators delivered as a single lot undergo epoxy application after one setup of the epoxy machine. Circulator staff therefore established lot sizes as the maximum number of circulators they could always epoxy in a single day. Unfortunately, the staff cannot fulfill a delivery with hundreds of "small lots," if there is variation across the lots. In short, the keys to reducing lot sizes are:

- Reducing setup costs by streamlining setup processes
- Completely resolving variability induced by setups, particularly on one particular epoxy machine

Once the staff resolves setup variability and makes progress towards reducing setup costs, they can entertain the option of lowering lot sizes. Circulator staff can achieve the ultimate goal of "single circulator flow" by a continuous focus on setup standardization and setup cost reduction. Until "single circulator flow" is viable, circulator staff can rely upon EOQ-style analysis to compute lot sizes. The EOQ approach for lot sizes closely resembles the EOQ approach for inventory reorder quantities. In more complicated cases, we introduce Lagrange multipliers to the standard EOQ technique to address capacity constraints.

10.4.1 Lot size calculation with EOQ

Before calculating lot sizes, we must ensure that the bottleneck resource has sufficient capacity to process the entire period's demand. In this calculation, we ignore setups. Assuming that sufficient capacity exists, we can use the standard EOQ approach to calculating lot sizes using Equation 4 below. While the index i denoted a component type in the inventory calculations, the index j denotes a circulator program in the lot sizing calculations. Thus, the EOQ for circulator program j equals EOQ(j)

$$EOQ(j) = \sqrt{\frac{2 \times K(j) \times \mu_{demand}(j)}{v(j) \times r}}$$

Equation 4: Inventory replenishment economic order quantity

10.4.2 Limitation of standard EOQ approach

In many cases, the optimal lot size for a circulator program is simply the EOQ for that program calculated on the bottleneck process. If setup times are relatively low or carrying costs are relatively high, then the EOQ method will yield small lot sizes. Based on the EOQ and the demand per period, we can calculate the number of lots (and therefore the number of setups). We then check that all resources have sufficient capacity to accommodate the setup and processing times for all programs. Clearly, as we reduce lot sizes, we increase the number of setups, and therefore we reduce the amount of capacity available for processing parts. If we find that insufficient capacity exists to accommodate all the setups, we must increase the "cost of setups." We can use Lagrange multipliers to increase these "cost of setups."

10.4.3 Lot size calculation with Lagrange multipliers

While the cost of setups equals *K(j)* with the standard EOQ approach, we redefine the cost of setups in the Lagrange multiplier approach as:

$$S(j) = K(j) + \lambda_1 \times T(j)$$

Equation 11: Setup cost with Lagrange multiplier

where

$S(j)$ = total setup cost for family j
λ_1 = Lagrange multiplier used to amplify the cost of setups on the bottleneck resource
$T_1(j)$ = setup time for family j on the bottleneck resource

We then substitute $S(j)$ for the original $K(j)$ into the EOQ formula. We start with a "small" value for λ_1. The EOQ formula becomes:

$$EOQ(j) = \sqrt{\frac{2 \times S(j) \times \mu_{demand\_j}}{v(j) \times r}} = \sqrt{\frac{2 \times [K(j) + \lambda_1 \times T_1(j)] \times \mu_{demand}(j)}{v(j) \times r}}$$

Equation 12: EOQ with Lagrange multiplier

We then incrementally increase λ_1 until the EOQ for each program is just large enough for sufficient capacity to exist. Appendix 3 shows an example of the lot sizing technique using Lagrange multipliers. A few important notes regarding this technique are:

- The Lagrange multiplier represents the marginal benefit (known as the shadow price) of additional capacity. Thus, we would be willing to pay up to the numerical value of the Lagrange multiplier to obtain an additional unit of capacity.
- As λ_1 increases, the effective cost of setups increases. Therefore, lot sizes will increase, causing the number of setups to decrease. Therefore, more capacity is available for actual production.

- If we can satisfy the capacity constraint with $\lambda_1 = 0$, then the original EOQ formula would have sufficed; the bottleneck resource has sufficient capacity.
- If one resource, like an operator, performs several processes on each program, then *K(j)* should equal the sum of the setup times for each program. No other terms in the equations change.
- If the EOQs associated with λ_1 satisfy the capacity constraint on the bottleneck but force another resource to be overcapacity, we should then solve the problem with an additional Lagrange multiplier (λ_2, λ_3, *etc.*) for each overcapacity resource. Thus, if two resources constrain lot sizes, the new setup cost for family j would be:

$$S(j) = K(j) + \lambda_1 \times T_1(j) + \lambda_2 \times T_2(j)$$

Equation 13: Setup Cost with two Lagrance multipliers

where:

λ_2 = Lagrange multiplier used to amplify the cost of setup on the second resource

$T_2(j)$ = setup time for family j on the second resource

The optimization would then involve iterating both Lagrange multipliers to find a solution that satisfies each resource constraint.

10.4.4 Lot size summary

Lean manufacturing unambiguously advocates the reduction in lot sizes and establishes the goal of single piece flow. Until setups are completely standardized, we unfortunately cannot change lot sizes. Once process engineering achieves this standardization, however, the circulator staff can enjoy the benefits of reduced lot sizes. The staff can adopt the simple EOQ approach if sufficient capacity exists. If capacity constraints preclude this simple solution, the staff can use the Lagrange multiplier technique to solve their lot sizing problem.

Through continuous improvement, process engineering will hopefully reduce setup costs. Revised EOQ calculations will yield smaller lot sizes. After significant improvement, single piece flow may be possible.

10.5 Launch plan

A prerequisite to implementing the conwip system is a scheduling tool to create a launch plan. A plan that schedules the release of kits without regard for the current production status will only cause confusion and increase WIP. However, by accommodating the same pull logic used in the conwip system, a launch plan can prevent these problems while also accurately predicting when resources are needed and when jobs will finish. Since cycle times and process steps vary by circulator family, the Operations Manager can use the scheduling tool and simple rules to sequence jobs to minimize the chances that the bottleneck will starve.[11] A hypothetical schedule is shown in Figure 11.

ID	Task Name	Duration	Start	Finish
25	**Program 2**	**11.7 days**	**Tue 1/13/04**	**Thu 1/29/04**
26	Assy pre-WB part I	1 day	Tue 1/13/04	Wed 1/14/04
27	Assy pre-WB part II	2.7 days	Fri 1/16/04	Wed 1/21/04
28	WB (Wirebond)	1 day	Wed 1/21/04	Thu 1/22/04
29	Assy post-WB	1 day	Thu 1/22/04	Fri 1/23/04
30	Test + operator review	4 days	Fri 1/23/04	Thu 1/29/04
31	**Program 3**	**10 days**	**Wed 1/21/04**	**Wed 2/4/04**
32	Assy pre-WB part I	1 day	Wed 1/21/04	Thu 1/22/04
33	Assy pre-WB part II	2 days	Fri 1/23/04	Tue 1/27/04
34	WB (Wirebond)	1 day	Tue 1/27/04	Wed 1/28/04
35	Assy post-WB	1 day	Wed 1/28/04	Thu 1/29/04
36	Test + operator review	4 days	Thu 1/29/04	Wed 2/4/04
37	**Program 1**	**11 days**	**Tue 1/27/04**	**Wed 2/11/04**
38	Assy pre-WB part I	1 day	Tue 1/27/04	Wed 1/28/04
39	Assy pre-WB part II	1 day	Thu 1/29/04	Fri 1/30/04
40	WB (Wirebond)	1 day	Fri 1/30/04	Mon 2/2/04
41	Assy post-WB	2 days	Mon 2/2/04	Wed 2/4/04
42	Test + operator review	5 days	Wed 2/4/04	Wed 2/11/04
43	**Program 3**	**12.1 days**	**Fri 1/30/04**	**Tue 2/17/04**
44	Assy pre-WB part I	1 day	Fri 1/30/04	Mon 2/2/04
45	Assy pre-WB part II	2 days	Wed 2/4/04	Fri 2/6/04
46	WB (Wirebond)	1.1 days	Fri 2/6/04	Mon 2/9/04
47	Assy post-WB	2 days	Mon 2/9/04	Wed 2/11/04
48	MP-RTP test + operator review	4 days	Wed 2/11/04	Tue 2/17/04
49	**Program 1**	**12.2 days**	**Fri 2/6/04**	**Tue 2/24/04**
50	Assy pre-WB part I	1.1 days	Fri 2/6/04	Mon 2/9/04
51	Assy pre-WB part II	0.9 days	Wed 2/11/04	Thu 2/12/04
52	WB	1 day	Thu 2/12/04	Fri 2/13/04
53	Assy post-WB	2 days	Mon 2/16/04	Wed 2/18/04
54	Test + operator review	4 days	Wed 2/18/04	Tue 2/24/04

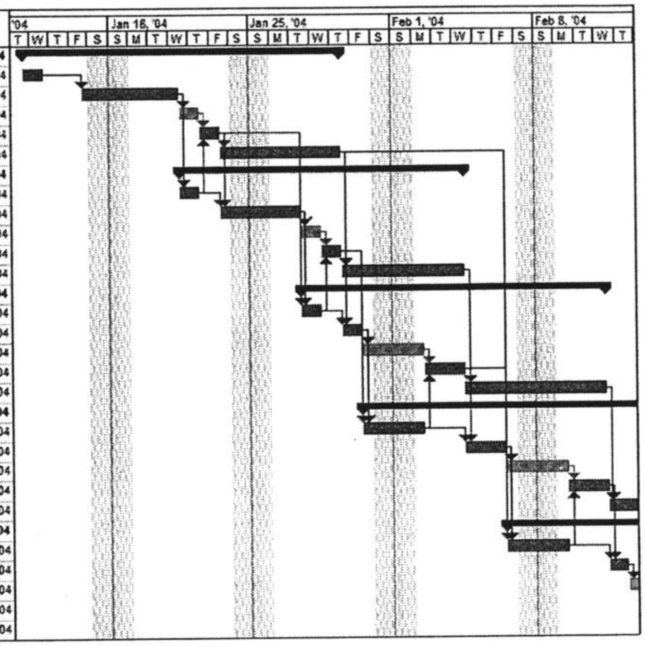


Figure 11: Hypothetical schedule

10.6 Metrics

Metrics help stakeholders gauge their progress towards attaining the broader organization's goals. Since different groups may have different objectives (e.g. engineering may intrinsically place more importance on innovation, and operations may intrinsically place more importance on execution), common metrics will begin the alignment process of different groups. (Cultural and political alignment are clearly required, as well.)

Stakeholders will more likely understand and internalize a set of metrics if the list is short and simple. It is therefore impractical, and probably counterproductive, to create a metric to measure every desired behavior. The ensuing complexity and confusion will prevent stakeholders from understanding the simple link between their actions and the organization's success.

While the circulator vision statement has five elements (as discussed on page 21), only three are independent and completely within the control of the circulator stakeholders. (The use of scheduling and quality tools helps create a more predictable production

[11] Because of the large variation in cycle times and process flows, the bottleneck may starve for short periods of time even under ideal conditions. While increasing the amount of allowable WIP can eliminate starvation, increasing WIP can also cause the same problems that plagued the production area earlier. Since the bottleneck may only starve for a few hours over the course of a few weeks, the proposed system was deemed acceptable by stakeholders.

system, and the integration of the value stream is an important, but broad objective, which must be monitored at a higher level.)

The first element of the vision statement calls for a predictable production system. Metrics which measure predictability are:

- *Lead time:* If the actual lead time for circulator programs is less than or equal to the expected lead time, the organization can create a reliable launch plan that will meet delivery deadlines. Predictable lead times therefore reduce the schedule risk for the overall value stream.
- *Variability in lead time:* Consistent lead times either indicate that problems do not occur or that problems are resolved quickly. Consistency is therefore an excellent metric of the organization's health.
- *On-time delivery percentage:* While obviously related to lead times, this easily computed percentage is a direct indicator of customer satisfaction.
- *Yield:* Tracking how many circulators fail operator reviews and test will help isolate problems within the production process. Since bottleneck throughput sets the maximum possible system throughput, correcting defective processes upstream of the bottleneck is critical.

The vision statement also explicitly recognizes the need for engineering development to coexist with production. Since daily management of the facility is transitioning from the Engineering organization to the Operations organization, the Operations staff must ensure that it provides Engineering staff with ample access to resources. Tracking Engineering usage therefore provides all stakeholders with a record. Metrics of Engineering utilization are:

- Engineering hours/week: This metric is a proxy for the amount of innovation that the facility supports. Since continued innovation is critical to meeting future customer needs, a drop in this metric over several months may warrant attention. Clearly, management must ensure that this metric is not gamed.

Lastly, the vision statement recognizes the importance of efficient resource use. Tracking resource utilization is often a dangerous metric, however, because it can motivate people to use resources at the expense of building excess WIP. Lean manufacturing textbooks therefore actually caution organizations against tracking resource utilization.

Since the circulator demand is quickly growing, however, the circulator takt time will soon be less than the current circulator cycle time. Instead of responding to this challenge by purchasing new equipment, production staff should ensure that they are using current resources efficiently. Since the bottleneck resource sets the maximum system throughput, the bottleneck must be efficiently used. It is critical to stress, however, that the bottleneck must be used judiciously: building WIP for the sake of increasing bottleneck usage is a poor decision.

Metrics which can help the organization understand and improve its resource use are:

- *Bottleneck overall equipment effectiveness*: Overall equipment utilization (OEE) measures the percentage of available time that a resource is creating parts that meet quality standards (Gellings, 2001). The formulae for OEE are:

$$OEE = availability \times performance\_rate \times quality\_rate$$

$$availability = \frac{actual\_operating\_time}{possible\_operating\_time}\ ^{12}$$

$$performance\_rate = \frac{actual\_cycle\_time}{theoretical\_cycle\_time}$$

$$quality\_rate = 1 - \frac{\#\_of\_rejects}{\#\_produced}$$

Equation 14: OEE formulae

  In essence, availability reflects unplanned downtime, performance rate reflects operating speed, and quality rate reflects the reliability of the process.

  World class availability is greater than 90%, world class performance is greater than 95%, and world class quality is greater than 99%. World class OEE is therefore greater than 85%.
- *Touch hours/unit:* Even though operators are currently not the bottleneck resource, labor charges are a major overall cost component. Thus, tracking labor hours will not only help management validate their bids for new jobs but also emphasize the relationship between productivity improvements and profitability.

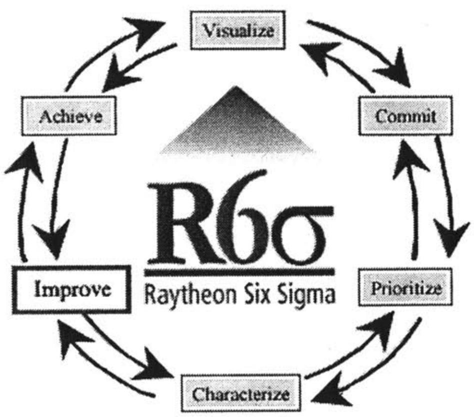
While these metrics will make the drivers of overall profitability more transparent to all stakeholders, these metrics are not all-inclusive. In fact, it is difficult, if not impossible, to write an equation to describe the optimal employee behavior in terms of quantifiable metrics. Since people can easily game metrics, qualitative judgments are necessary as well. Some important indicators of health will therefore unfortunately remain unmeasured.

Armed with this detailed plan for the future state, we are now ready for implementation.

[12] Actual operating time = possible operating time – unplanned downtime due to equipment failures, setups, material shortages, etc. Possible operating time = total working time – planned downtime

11. Step V - Improve

Plans are only good intentions unless they immediately degenerate into hard work – Peter F. Drucker[13]



In the fifth stage in the Raytheon Six Sigma™ process, we implement our proposed solution. The implementation phase of this lean initiative requires us to:

1. Build awareness of the future state
2. Empower individuals
3. Squeeze more from existing resources
4. Fix problems quickly
5. Implement visual tools

and

6. Sustain the gains

11.1 Build awareness of the future state

Building awareness of lean tools and clarifying misconceptions is a critical step that we can accomplish through conversations, simple visual tools, and practice. While the initial pilot program failed to generate sustainable improvements, it helped operators realize that a first-in-first-out philosophy reduces queue times and thus lead times. The operators even enjoyed working on one job instead of several jobs simultaneously. One operator remarked, "I like the way you stay focused on one thing at a time. When your brain is going in several different directions, you're really not able to give it your best." Through simple, hands-on games using Lego® blocks, operators discovered that reducing lot size decreases lead time and rework.

When the Directors of Engineering and Operations articulated a common vision, defined metrics, and delineated roles and responsibilities, the lean initiative gained traction. By participating in meetings and vocalizing their support, the perceived importance of the lean initiative increased dramatically.

11.2 Empower individuals

Leadership must empower key stakeholders (especially the circulator Operations Manager) to make decisions that affect programs that are production-ready and programs that are in engineering development. Since engineering stakeholders are accustomed to deciding which circulators deserve priority, the transition of authority to the Operations

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[13] Source: http://www.brainyquote.com/quotes/quotes/p/peterfdru131070.html accessed on April 27, 2004.

Manager may not be a smooth process. Continued leadership support will obviously aid the transition of authority.

11.3 Squeeze more from existing resources

By eliminating waste (often in the form of rework) from each process, the team can sometimes preclude the need for procuring additional resources. If resource requirements still exceed the number of resources available, management can attempt to level load by producing future requirements during periods of lower demand.

The Theory of Constraints stresses that throughput of the bottleneck resource sets the maximum possible system throughput. It is critical that valuable bottleneck time is not wasted processing defective parts. Therefore, yields upstream of the bottleneck and at the bottleneck must be maximized. In the case of circulators, application of this theory of constraints principle led to a concerted effort to improve the wirebond process. By mapping defects back to contamination, process engineers successfully improved wirebond yields and thereby reduced wirebond cycle times by approximately 20%.

11.4 Fix problems quickly

Lean and six sigma share an emphasis on continuous improvement to ward off the dangers of complacency. Since customers will likely raise their expectations in the future, the circulator production facility must ingrain continuous improvement in its culture. The continued discovery and rapid resolution of problems will ensure that the lean initiative meets both current and future challenges.

Steady work loads, WIP levels, and throughput are symptomatic of stable systems. By contrast, a system which oscillates between extremes likely suffers from underlying problems and frustrated workers. For example, delays in identifying problems, delays in deciding on corrective actions, and delays in implementing proposed solutions can cause oscillations, as shown in Figure 12.

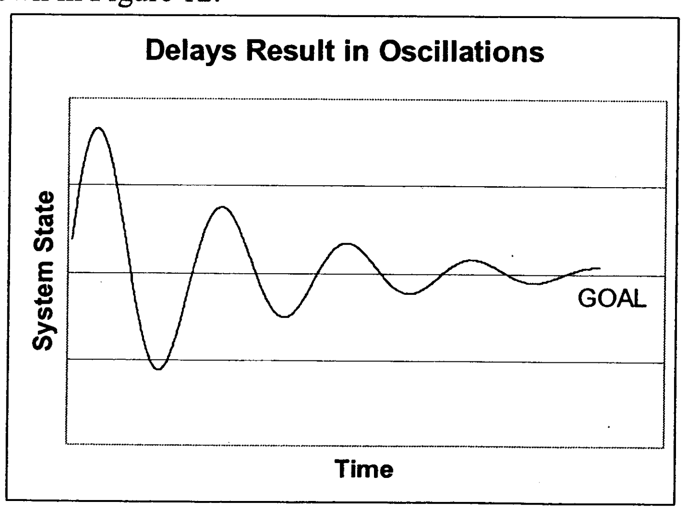


Figure 12: Oscillations in system state

The dynamics behind the oscillations are shown in the causal loop diagram shown in Figure 13 (Sterman, 2000, p. 114). A large "discrepancy" results in a large "corrective action" (denoted by the plus sign). This large "corrective action" results in a large change in the "state of the system." A large change in the "state of the system" greatly reduces the "discrepancy." If delays are large, oscillations will be large and will also persist. By reducing delays, the team will reduce the magnitude and duration of oscillations. In a more stable system, staff will not spend its time "fire-fighting" and can instead focus on (and benefit from) continuous improvement.

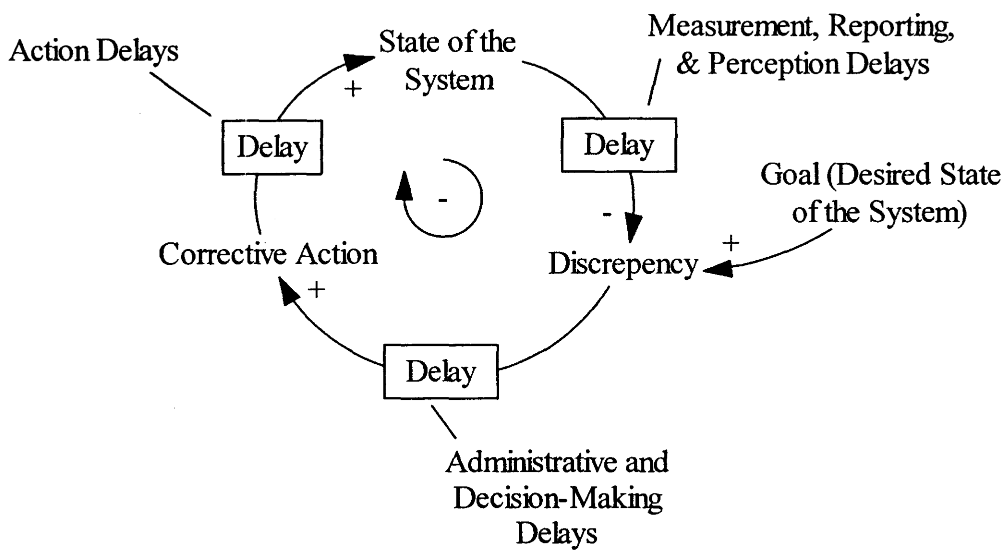


Figure 13: Delays cause oscillations

11.5 Implement visual tools

Visual tools greatly facilitate the reduction of these "measurement, reporting, and perception delays" (Sterman, 2000, p. 114). More broadly, we can use visual tools to:

- Explain the production system's design
- State the expected duration of specific tasks
- Instantly communicate the status of on-going jobs.

Moreover, "visualization capitalizes on our innate strengths and compensates for our limitations by shifting most of the burden on memory to powerful perceptual processes. This enhances the process of analysis and discovery by allowing us to detect patterns, make connections and comparisons, and draw conclusions from large amounts of data" (Ping, 1996, pp. 7-10). In short, visual tools help operators process the barrage of data they encounter in a factory. Therefore,

> "[the] design of complex manufacturing systems should thus take into account not just traditional industrial engineering requirements, such as modeling material flows and the efficient use of resources, but also metrics, incentives, and the interplay of workers and machinery -

especially information systems that workers use to guide their actions in the production environment" (Smith, 2003, p. 113)

In an effort to capitalize on these benefits, the Operations Manager has created and deployed simple visual tools. The graphics shown in Figure 14 clearly describe both current and target yield and lead time for a certain program.

Production Yield　　　　Lead Time

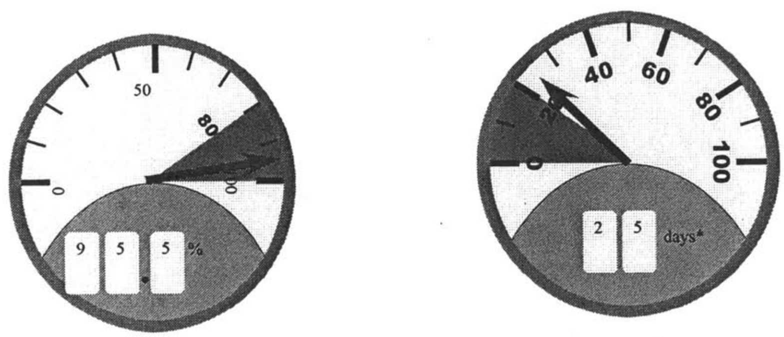


Figure 14: Circulator visual tools

The Operations Manager has also established and published the expected duration for each program. A sheet, color coded to each specific program, now accompanies each lot and explains its expected duration. Figure 15 shows an example of one sheet for a fictional circulator program. The duration of each task is fabricated.

Expected Durations for Progam X

START DATE: ________

	Assy & Test Processes	Expected (hrs)	% Complete	"X" = Complete	Days Left
PRE WIRE BOND	Prepare documentation				
	Prepare fixture	3.0			
	Place carriers				
	Seat carriers		8%	________	3.2
	Screen print epoxy				
	Place substrates	9.6			
	Cure @T1		34%	________	2.3
	Place magnet/spacer assemblies				
	Cure 2	6.5			
	Cure @T1		52%	________	1.7
WIRE BOND	Plasma Clean				
	Wire bond resistors	8.5	75%	________	0.9
POST WIRE BOND	Edge Seal				
	Cure 2				
	Cure @T1	10.1			
	Delaminate fixture				
	Review		100%	________	0.0
	Total Assy	**36.7**			
TEST	Test	12.0			0.1
	Pack for shipment	1.0			0.0
	Total Test	**13.0**			

Figure 15: Expected durations

11.6 Sustain the gain

The implementation of a lean initiative must contain provisions to sustain realized gains. Clearly, vocal and continued commitment by Raytheon's leadership is critical to ensuring that stakeholders do not view lean as yet another passing fad. Because of previous "initiatives du jour," one particularly amusing response we heard was, "been there…done that…didn't like it." Since lean initiatives require changes in the organization, culture, and political landscape, implementing lean initiatives will require time. Patience and continued support are essential.

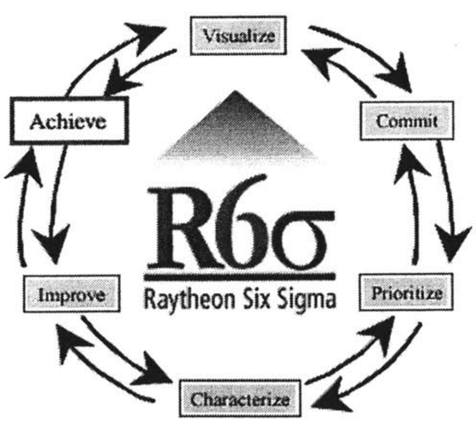
Change agents must overcome two major obstacles in order to sustain the gains. First, they must convince skeptics that the initiative is robust and that the team can solve problems as they arise (Senge et al, 1999, p. 27). These skeptics may cite production problems that will inevitably occur to bolster their opposition to the lean transformation. While preventing problems remains critical, the Operations Manager should openly share problems with all relevant stakeholders. If change agents feel that problems should remain secret, the initiative will likely fail. The quick resolution of problems through aggressive root cause analysis will help convince skeptics that lean manufacturing works, even in circulator production.

Second, change agents must link tangible improvements (like lead time reduction) to more traditional methods of measuring success (like cost reduction) (Senge et al, 1999, p. 27). In the past, few production-type metrics were regularly collected. Instead, stakeholders knew they were successful if new customers ordered circulators, returning customers continued to order circulators, and Raytheon's circulators were less expensive or more capable than competitors' circulators. People will continue to challenge the initiative if it does not yield results that are traditionally valued. Therefore, management must convert tangible results into the language understood by existing stakeholders. For example, if skeptics see productivity increase as a result of the initiative, they will be less likely to oppose the effort.

By definition, sustaining the gains requires continuous effort. More broadly, lean and six sigma processes emphasize continuous improvement. At some point during the implementation phase, however, we must assess our achievements and note the challenges that remain. The sixth step in Raytheon Six Sigma™ helps us with this step.

12. Step VI - Achieve

Aviation is proof that given the will, we have the capacity to achieve the impossible. – Eddie Rickenbacker, American aviator[14]



The sixth and final step in the Raytheon Six Sigma™ process is celebrating achievements, documenting challenges, and recognizing key supporters of the change initiative.

12.1 Lead time reduction

As of this publication, the circulator lean initiative was still in the implementation phase. Data is therefore limited. Early results suggest a greater than 50% reduction in the lead time for one high volume program. With continued improvement, a 70% reduction is possible for that program.

12.2 Productivity improvements

Ultimately, a lean production system is only successful if it enables higher throughput or lowers production costs. Often, a properly implemented lean production system will achieve both simultaneously. Higher throughput often results from quicker problem

[14] Compiled by Dormann, Henry O., The speaker's book of quotations, New York: Fawcett Columbine, 1987. P. 149

resolution and quicker redeployment of resources to increase bottleneck capacity. Cost savings result from several avenues including reduced rework, reduced inventory carrying costs, and increased productivity. While it is relatively easy to understand how lean principles can lead to a reduction in rework and a reduction in inventory, it is somewhat more difficult to establish a causal relationship between WIP reduction and increased productivity.

Qualitative statements are easy: a reduction in WIP simplifies production and helps operators focus on tasks critical to maintaining high throughput levels. Quantifying these benefits is, however, difficult. Nonetheless, quantifying these benefits is critical to gaining the support of skeptics who question the benefits of lead time reduction. One body of research suggests a 2:1 ratio between lead time reduction and productivity improvements. Therefore, a company which reduces its lead time by 50% will also enjoy a 25% increase in productivity (Meredith, McCutcheon, & Hartley, 1994, pp. 7-22.) Another body of research suggests almost a 1:1 ratio between lead time reduction and productivity improvements:

> Based on years of benchmarking and observation in organizations around the world, we have developed the following simple rules of thumb: Converting a classic batch-and-queue production system to continuous flow with effective pull by the customer will *double labor productivity* [italics added] all the way through the system (for direct, managerial, and technical workers, from raw materials to delivered product) while *cutting production throughput times by 90 percent* [italics added] and reducing inventories in the system by 90 percent as well. Errors reaching the customer and scrap within the production process are typically cut in half, as are job-related injuries. Time-to-market for new products will be halved...(Womack & Jones, 2003, p. 27).

Since reliable circulator productivity data is currently unavailable, we can only predict productivity improvements. Using the 2:1 heuristic, the 50% reduction in lead time for the program cited earlier may improve productivity for that program by 25%. The target 70% reduction in lead time may improve productivity by 35%.

For reference, other organizations in a variety of industries have published direct improvements in productivity that stem from their lean initiatives. Table 3 summarizes the actions and results from a few companies. The average lead time reduction to productivity improvement ratio from Table 3 is 2.5:1, and is therefore fairly consistent with the 2:1 heuristic.

Company	Actions	Results
Amtech (fiber glass and vacuum formed part manufacturer)[15]	• Reduce lot sizes • Implement pull • Reduce WIP by 53%	• 63% reduction in lead time • 21% increase in productivity
Blue Sea Systems (marine electrical component manufacturer)[16]	• Simplify production processes • Implement single piece flow • Reduce setup times • Use point of use storage	• 86% reduction in lead time • 47% increase in productivity • 75% reduction in WIP
Barnes Aerospace Ogden Division (aircraft component manufacturing)[17]	• Reduce setup time • Implement 5S • Implement pull	• 61% reduction in lead time • 24% increase in productivity • 67% reduction in space requirements • 45% increase inventory turns

Table 3: Productivity improvements from lean

12.3 Challenges ahead

As can be expected, the team encountered difficulties during the implementation phase. Technical problems with a critical test machine required several months to resolve and resulted in long circulator lead times. A few work stoppages occurred due to component availability and cleanliness. Changes in certain epoxy materials led to problems which significantly reduced yield. While these problems frustrated the team, the team resolved the problems as quickly as possible. So long as they continue to identify and resolve problems quickly and fully, the team will succeed. Continued patience and vocal support from management is critical.

12.4 Hypothesis validation

Since the implementation of this lean initiative only started two months ago, it is too early to prove that it has succeeded. The marked reduction in lead time is a very positive indicator. Staff has also commented that WIP is visibly reduced. The ultimate litmus test, however, is whether:

- Metrics continue to improve
- Stakeholder needs are met
- Skeptics begin to embrace the change
- Customers receive their circulators on-time and on-budget

[15] Source: http://www.gemba.com/ourwork_fiberglass.htm accessed on 07 March 2004
[16] Source: http://www.gemba.com/ourwork_electrical.htm accessed on 07 March 2004
[17] Source: http://www.gemba.com/ourwork_aerospace.htm accessed on 07 March 2004

We currently lack the data to accept or reject our hypothesis. Since the production area involves people, we most likely can never establish a causal relationship between our root cause analysis and success of our lean initiative. With time however, we can ascertain whether our analysis and actions prevent problems from recurring. If problems do not recur and if the criteria above indicate a successful initiative, we may at least claim that our hypothesis is not rejected.

12.5 Recognition of key stakeholders

A successful change initiative requires the willingness of stakeholders to forgo their familiar routines and try something different. Thanking these stakeholders is critical since continuous improvement will likely be contingent upon their support in the future. While financial rewards are helpful, non-financial recognition can also be effective. Personal gratitude from senior leaders is a powerful tool that is often underused. Fun events like celebrations create lasting memories that build relationships.

13. Getting to lean enterprise

The correct use of lean manufacturing principles alone will yield great benefit to the organization. Through solving the root causes of current production problems, we can eliminate waste and ensure that existing resources are efficiently used. The next quantum step in the lean journey, however, is achieving lean enterprise. Lean enterprise is defined as "a business organization that delivers value to its stakeholders, with little or no superfluous consumption of resources (materials, human, capital, time, physical plant, equipment, information, energy)" (Bozdogan et al, 2000, p. 22)

An organization can apply lean principles beyond the walls of its production floor. For example, the concept of single piece flow applies to administrative paperwork, the concept of inventory minimization applies to office supplies, and the concept of early defect detection and resolution applies to engineering design (Bozdogan et al, 2000, p. 14). Lean principles also extend to suppliers. Through engaging suppliers in setting appropriate inventory levels, an organization can benefit from "improved inventory turns, higher service levels, reduced operating costs and mutually beneficial manufacturer-supplier partnerships" (Bravo, 1999, p. 3). Supplier managed inventory is not an instant panacea, however. It must be carefully structured as benefits vary by company. One study concludes that the "biggest gains go to those who can fundamentally change their processes and establish means to efficiently and frequently exchange information" (Bravo, 1999, p. 114). Methods of communicating with suppliers include electronic kanban signals, barcodes, and enterprise resource planning (ERP) software.

13.1 3-D concurrent engineering

In an era characterized by transient competitive advantages, companies can no longer focus on product design, process improvements, or supply chain development in isolation (Fine, 1998, p. 133). The term "3-D concurrent engineering," coined by MIT Professor Charlie Fine, describes the growing need for concurrent engineering of these three functions. "When firms do not explicitly acknowledge and manage supply chain design and engineering as a concurrent activity to product and process design and engineering, they often encounter problems late in product development, or with manufacturing launch, logistical support, quality control, and production costs" (Fine, 1998, p.133). Companies must therefore evolve their supply chains to meet new programs' needs and take advantage of new supplier capabilities. A static view of a supply chain based on historical capabilities will yield a suboptimal and uncompetitive result.

Raytheon's antenna systems are modular at the system level but highly integrated at the subsystem level. For example, the integration of circulators into "stick" assemblies requires a fair degree of precision; operators must maintain fairly tight tolerances between critical features on the circulators and critical features on the "stick" housings. Minor errors result in significant (and costly) rework. Operators are also currently forced to manually remove conversion coating, a treatment used to prevent corrosion, from critical wirebonding surfaces. This time consuming removal process is the result of insufficient cooperation between design engineers, process engineers, and suppliers of the "stick" housings. Charles Fine states, "product and supply chain architectures tend to be aligned along the integrality-modularity spectrum. That is, integral products tend to be developed and built by integral supply chains, [and] modularity in product architecture enables manufacturers to use modular supply chains" (Fine, 1998, p. 140). When integral products are not developed by integral supply chains, the result is a costly solution.

If Raytheon continues to optimize performance through developing highly integral subsystems, it should strongly consider integrating its supply chain through geographic, organizational, cultural, or electronic means (Fine, 1998, p. 137). Geographical proximity, created by physical location, facilitates face-to-face communication. Organizational proximity, fostered through common ownership or managerial control, helps align incentives. Cultural proximity, created by common languages, laws, and ethical standards, builds trust. Finally, electronic proximity, generated by virtual communication, facilitates information flow.

13.2 Enterprise-level metrics

The strategic design lens reveals the importance of metrics to align the behaviors of different groups "linked" on a common project. At the enterprise level, common metrics "align the programs and the manufacturing organization to pursue the same objective [and thereby]...improve the financial performance of the enterprise as a whole" (Nicol, 2001, p. 21). It will be difficult for senior management to agree to a common set of metrics that suits product design, process design, and supply chain. This difficulty is evidence that these three functions have historically not been aligned. Just as all other processes benefit from continuous improvement, management must periodically evaluate the metrics' efficacy in promoting the desired behaviors.

13.3 Human Resources

Human resource theory advocates that companies first create a business strategy that achieves their objectives, and then identify critical success factors that will enable a company to implement that strategy, and finally implement human resource practices to achieve the critical success factors. To achieve Raytheon's vision of being "the most admired defense and aerospace systems supplier through world-class people and technology," (Brassard & Ritter, 2000, p. *b*) it has established a strategy which focuses on customer needs, operational excellence, global growth, and leveraging existing strengths. If Raytheon decides that lean enterprise is a key success factor, then human resources must identify the skills needed to create a lean enterprise.

Succinctly put, "Lean people make a lean enterprise![18]" Clearly, lean expertise alone is not useful. People must combine their industry experience, technical knowledge, lean thinking, and interpersonal skills to make significant contributions to the organization. Skills that people must develop include:[19]

- *Customer focus:* Employees must know their customer, whether external or internal to the organization. They must understand their customers' needs, even when they change. Finally, employees must know whether their customers' needs are being met.
- *Enterprise-level thinking:* Employees must understand how various processes fit in the larger value stream. Skills in "process mapping, process measurements, and process redesign," are prerequisites to proactively fixing problems. When redesign is required, "lean people set aside their parochial concerns and think about what's best for the entire enterprise."
- *Flexibility:* Employees must be open to change. Evolving customer demands will require new products and processes which render the familiar obsolete.
- *Initiative:* Employees must aggressively "identify waste and…eliminate it quickly." To stay competitive, lean "people take the initiative to maximize their productivity, manager their time, and stay organized."
- *Innovativeness:* Employees must embrace continuous improvement. The competition is unforgiving.
- *Ability to team:* Employees must learn to team with others to resolve problems instead of waiting for direction. "Management in a lean enterprise needs to know how to establish, charter, nurture, reward, and manage collaborative groups."
- *Leadership:* Employees must learn to lead, even without formal authority. By empowering individuals at all levels of the hierarchy to make decisions, organizations benefit from quicker decision making and fewer "oscillations." Therefore, companies need individuals who can "set the direction that other people follow."

The importance of solid leadership is a recurring theme, and is especially important in a change initiative. Leaders must (Bozdogan et al, 2000, p. 27):

- "Develop and communicate a vision for Lean"
- "Create an environment for change and transformation across the Enterprise"

[18] Howardell, Doug, *Seven Skills People Need to Create a Lean Enterprise*, p. 1 available at http://www.edi.gatech.edu/Lean/Lean_Articles/leanarticles-sevenskills.cfm.
[19] *ibid*, pp. 3-7.

- "Develop Enterprise-level goals and metrics that encourage and promote Lean"
- "Identify and support change agents"
- "Promote leadership and risk taking at all levels"
- "Empower teams and individuals"
- "Commit and train resources"
- "Nurture the transformation process"
- "Remove barriers"

and, most important[ly]

- "Lead the Enterprise transformation"

14. Conclusion and next steps

A man's mind, stretched by a new idea, can never go back to its original dimension.
- Oliver Wendell Holmes[20]

Lean manufacturing is not new to Raytheon. A previous team successfully applied lean principles to MIC production, and our team is applying lean to circulator production. Since success begets success, it is critical that the management partner with the circulator staff to ensure the initiative's success. With each successive implementation, Raytheon lowers the barriers to change.

Recognizing the importance of optimizing the overall system, SAS' management team has dedicated one 2005 LFM internship to substrate production. As shown in Figure 16, substrates are the building blocks for higher level assemblies. These assemblies include MICs, circulators used in active arrays, and circulators used elsewhere. Improvements in substrate production will directly help these higher level assemblies meet their cost and schedule goals. In addition, lean thought will continue to permeate throughout the organization, enabling Raytheon to continue its lean journey and ultimately achieve the greater goal of lean enterprise.

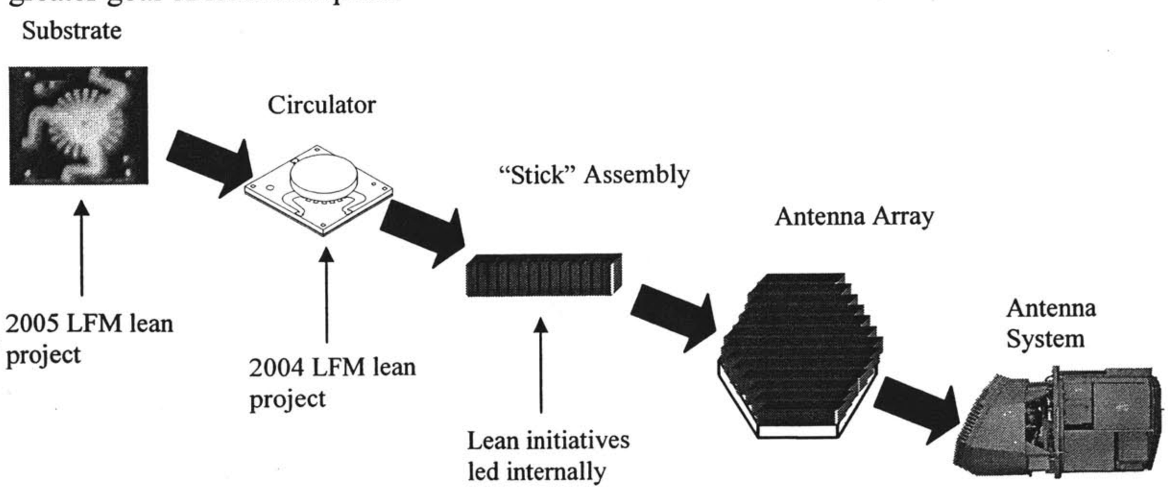


Figure 16: Next steps for lean implementation

[20] Source: http://home.att.net/~quotesexchange/oliverwendellholmes.html accessed on April 4, 2004.

Appendix 1: Capacity model

Mapping the value streams for each circulator program enables us to create circulator families based on similarities in cycle times and process flows. Armed with cycle time data for each family and estimated future demand for each program, we can compute resource requirements by using the following variables:

#_shifts_per_month	= number of shifts per month
Demand(j)	= quantity of circulators demanded for program *j* per month
CT(p,j)	= cycle time per circulator on process *p* for program *j*
engin._ratio	= estimated percentage of time resources will be dedicated for engineering development
setup_time(p,j)	= setup time on process *p* for program *j*
target utilization	= percentage of total time a resource is available after allotting time for preventative maintenance and unplanned downtime
working time/shift	= number of hours per shift minus break times

The total production time for one lot of program *j* on a given resource is given by Equation 15.

$$Time\_per\_lot(j) = Lot\_size(j) \times \sum_{process(p)} CT(p,j) + \sum_{process(p)} Setup\_time(p,j)$$

Equation 15: Total resource time required per lot

The amount of time available on a resource per month equals:

$$Available\_Time = \#\_shifts\_per\_month \times \frac{working\_time}{shift} \times target\_utilization \times (1 - engin\_ratio)$$

Equation 16: Available time per month

The number of resources required therefore equals:

$$\#\_of\_resources\_required = \frac{\sum_{program(j)} Time\_per\_lot(j) \times Demand(j)}{Available\_time}$$

Equation 17: Number of resources required

Using these equations, we can plot the number of resources required over time, as shown in Figure 17. For clarity, the plot in Figure 17 only illustrates the requirements for four of the circulator resources.

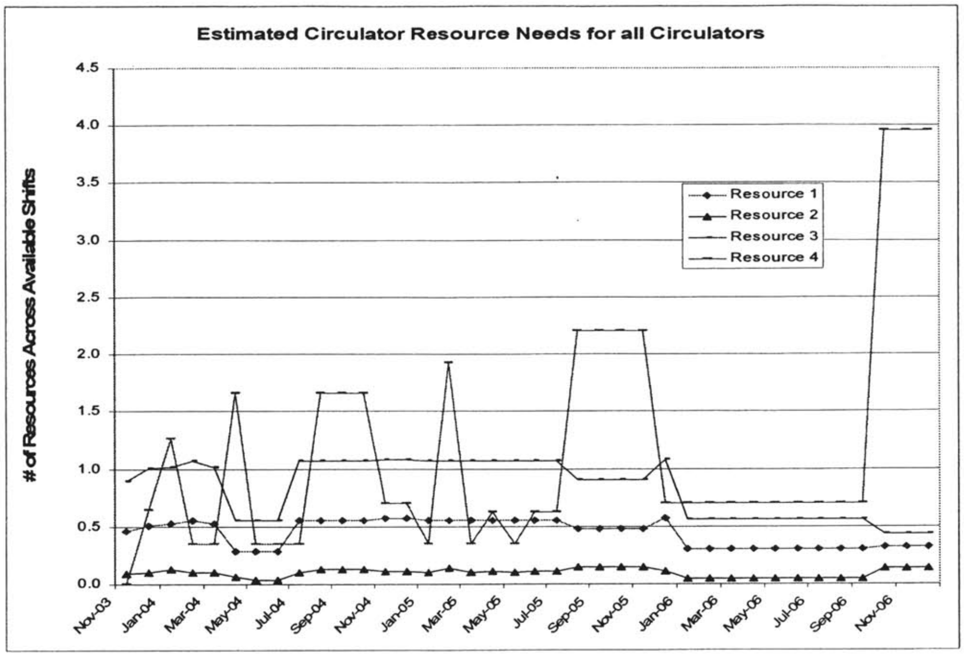


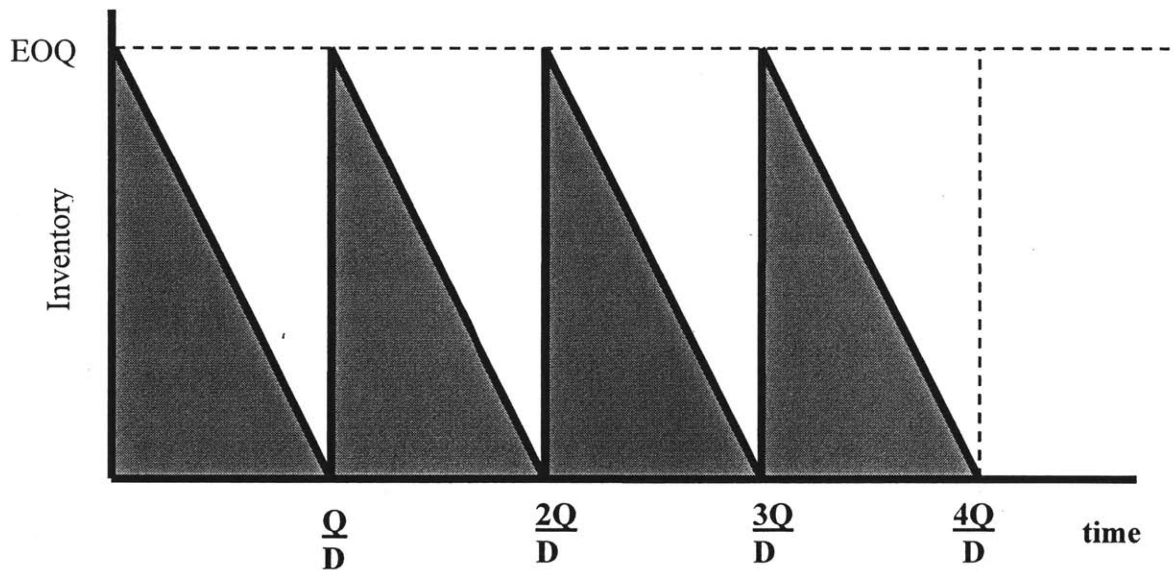
Figure 17: Capacity model resource estimates

Appendix 2: Derivation of Economic Order Quantity

(Taken from Roemer, 2002, pp. 21-26)

Let

K	= fixed order cost (or setup cost)
μ_{demand}	= average demand per period
r	= carrying charge (assumed constant for all inventory)
v	= unit cost
EOQ	= economic order quantity
TVC	= total variable costs



Average inventory per period $= \frac{EOQ}{2}$

Average inventory costs $= \frac{r \cdot EOQ}{2}$

Ordering costs $= \frac{K \cdot \mu_{demand}}{EOQ}$

Total variable costs $= \frac{r \cdot v \cdot EOQ}{2} + \frac{K \cdot \mu_{demand}}{EOQ}$

Find minimum total cost:

$$\frac{\partial(TVC)}{\partial(EOQ)} = \frac{r \cdot v}{2} - \frac{K \cdot \mu_{demand}}{EOQ^2} = 0$$

$$EOQ = \sqrt{\frac{2 \cdot \mu_{demand} K}{v \cdot r}}$$

Appendix 3: Lot size calculation using Lagrange multipliers

EOQ Approach

				Circulator Program: A	B	C	D	Totals	
A	Labor rate	70	$/hour						
B	Carrying charge	15%	r						
C	Available hours annually	1900	hours						
D	Setup time			1	2	0.5	1.5		
E = A*D	Setup cost			$ 70	$ 140	$ 35	$ 105		
F	Unit cost			$ 10	$ 300	$ 100	$ 200		
G	Demand (units/year)			10000	2000	25000	50000		
H	Cycle time (hours)			0.05	0.03	0.03	0.01		
I = G*H	Processing time/year			500	60	750	500	1810	hours
J = sqrt(2*E*G/[B*F])	EOQ			966	112	342	592		
K = G/J	# lots/year			10	18	73	85	186	lots
L = D*K	Setup time/year (hours/year)			10	36	37	127	210	hours
	Total time/year			510	96	787	627	2020	hours
M = A*L	Setup cost/year ($/year)			$ 725	$ 2,510	$ 2,562	$ 8,874	$14,670	
N = 0.5*J*F*B	Holding cost/year ($/year)			$ 725	$ 2,510	$ 2,562	$ 8,874	$14,670	
O = M+N	Total cost/year ($/year)			$ 1,449	$ 5,020	$ 5,123	$ 17,748	$29,341	
P = C - Total(I)	Available time for setups	90	hours						

	Circulator Lot Sizes Using Lagrange Multiplier				Resulting Annual Setup Times (hours)					Total Cost
Lagrange multiplier	A	B	C	D	A	B	C	D	Total	
0	966	112	342	592	10	36	37	127	210	$ 29,341
50	1265	146	447	775	8	27	28	97	160	$ 30,413
100	1506	174	532	922	7	23	23	81	134	$ 32,276
150	1713	198	606	1049	6	20	21	72	118	$ 34,283
200	1897	219	671	1162	5	18	19	65	107	$ 36,282
250	2066	239	730	1265	5	17	17	59	98	$ 38,228
300	2221	256	785	1360	5	16	16	55	91	$ 40,109
310	2251	260	796	1378	4	15	16	54	90	$ 40,478
								Increase in total cost		$ 11,137

Notes:

1 Using a Lagrange Multiplier of 310, we reduce the number of setups enough to meet the overall capacity constraint
2 Total Cost = Annual Setup Cost + Annual Holding Cost = Annual Setup Time*Labor Rate + 0.5*EOQ*Unit Cost*Carrying Charge

Conclusion

EOQ approach yields lowest cost answer. However, if insufficient capacity exists to perform all the required setups, we must increase lot sizes. Use Lagrange multipliers, we find the required lot sizes. In this fictional case, the increased lot sizes increases the cost of the overall solution by $11,137/year

Acronyms

Conwip	Constant work in progress
ERP	Enterprise resource planning
FIFO	First-in-first-out
MIC	Microwave integrated circuit
MRP	Material Resource Planning
WIP	Work in progress
RF	Radio frequency
SAS	Space and Airborne Systems
SSM	Solid State Microwave

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