

Effective Synchronization of MRP to Production During a Lean Transformation

By

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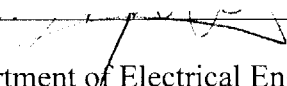
Submitted to the Sloan School of Management and the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the Degrees of

Master of Business Administration and
Master of Science in Electrical Engineering and Computer Science


In Conjunction with the Leaders for Manufacturing Program at the
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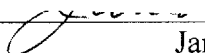
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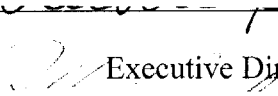
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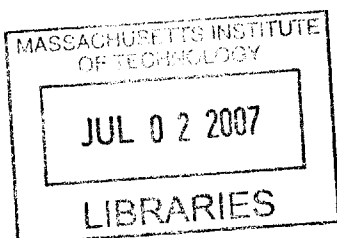

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ABSTRACT

Raytheon – Network Centric Systems (NCS) division develops and produces mission solutions for networking, command and control, battlespace awareness, and air traffic management. The facility in Largo, Florida, produces radios and their associated equipment for programs in the NCS division.

The Largo facility uses traditional Material Resource Planning (MRP) systems to drive supply chain and production output. This push system runs directly against lean principles of flow and pull during Raytheon’s continuous lean improvements. This tension makes the lean transition difficult for all aspects of the business.

This thesis specifically examines the reduction in throughput variability that comes with lean controls and shows that the lean principles of flow, pull and pursuit of perfection help MRP be more accurate by providing the stability required for the MRP system. This is especially important during the transition between a classic MRP push system and the more efficient use of material planning available in a lean organization. Results of the alignment between operations and MRP include lower lead times, lower inventory and lower cost production. This thesis also explores the fundamental cultural, structural and political issues with implementing certain lean changes and the effects of these issues on variability of the system.

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1.0 Introduction

This thesis examines how lean principles of flow and pull can provide the stability required to increase the accuracy of a Material Resource Planning (MRP) system. Since this was demonstrated in an actual manufacturing environment, an understanding of the corporation and business background is required.

1.1 Raytheon Largo

Raytheon Network Centric Systems, with 2005 sales of \$3.1 billion, develops and produces mission solutions for networking, command and control, battlespace awareness, and air traffic management. NCS provides its customers with unprecedented accuracy, speed, and Common Decision Engagement Capability.TM

The marketplace in which NCS operates consists of Air Traffic Management; Command and Control; Communications; and Networked Sensors. Each of these markets combines the core capabilities NCS offers to their customers in order to create a net-centric environment for business growth. These core capabilities are battlespace awareness, command and control, and networking. The business of NCS is driven by these technologies, and the systems and products that support them.¹

NCS maintains a manufacturing division in Largo, Florida, which is chartered to provide best-in-class manufacturing services and solutions. Operations in Largo manufacture products from NCS including radio receivers / transmitters, terminals, cables and

harnesses. Largo also provides integration, test, assembly, overhaul, repair and quick response capabilities for NCS. In general, the programs at Largo require assembly of pre-manufactured parts. These programs usually do not require significant amounts of circuit card manufacturing, large machining or metal fabrication. The value provided by Raytheon is the integration of diverse, complex components into a functional system. For these complex systems, a significant portion of the entire contract's value is in the system integration area.

This facility was opened in the late 1990's to support products and programs from Raytheon sites in Marlborough, MA; St. Petersburg, FL; Towson, MD; and Ft. Wayne, IN. This consolidation of manufacturing was designed to remove the inefficiencies associated with dispersed, small-scale operations. Program management and design activities remained in their dispersed locations to support their current customers. The Largo site has remained focused on production without increasing design or program management responsibility.

The Largo site employs approximately 300 salaried and 500 hourly personnel. The hourly personnel are represented by the International Union, United Automobile, Aerospace and Agricultural Implement Workers of America (UAW). However, only roughly half of the hourly employees belong to the union.²

The management team in Largo identified the following strategic goals for 2006:

- Improve responsibility, accountability and authority

- Implement Lean Manufacturing
- Improve Supplier Performance
- Improve alignment with sending sites
- Grow the Business

The research conducted in this thesis is aligned to the “Implement Lean Manufacturing” strategic initiative.

Each program in the manufacturing facility is associated with a separate contract with the United States government. Although each contract specifies many terms and conditions, the contractual performance metrics for Largo manufacturing are summarized by the management teams simply in terms of cost, quality and schedule.

COST

Although there are many costs and financial obligations associated with performance on a contract, there are only three main management concerns in production:

- **Fixed Costs**, including costs associated with facilities, equipment and overhead personnel. The management team continuously strives to bring in new business to spread these costs over a larger production base. This is generally not measured as a metric for the production lines.
- **Variable Labor Costs**, including the time in direct labor required to build each unit. This is measured in terms of the Hours Per Unit (HPU) metric for each item built in the plant. The management team ensures that each production worker has sufficient work to keep this cost low.

- **Inventory / Material Costs**, including the cost of materials and the inventory holding costs. This is measured in terms of a material cost metric and inventory turns. The management team works with the supply base to decrease the cost of materials and with the operations team to reduce inventory.

SCHEDULE

Each contract includes items known as Contract Line Item Numbers (CLIN), which describe deliverables and other important contractual items. Separate delivery dates and production quantities required by the government to the manufacturing center are outlined specifically in separate line items (or “CLINs” as commonly used in discussion). Therefore, CLIN on-time delivery becomes the most important schedule metric. The management team works to ensure that there are sufficient buffers in the system to ensure CLIN on-time delivery.

QUALITY

Each contract includes test and audit procedures ensuring that quality products are delivered to the government customers. Usually the required tests are performed on each unit and become part of the manufacturing process. Therefore, customer perception of manufacturing quality is very high, but is sometimes achieved by re-work of failed units. The amount of re-work required on each product line therefore becomes an important metric. The management therefore works constantly with the engineering sites to decrease the amount of re-work.

1.2 Organization and Authority Context

NCS is a matrix organization, including functions for operations, program management, business development, supply chain, six sigma, engineering, finance, quality, human resources, legal, and information technology. Each employee officially reports through one of these organizations, and is then assigned to cross-functional teams to fulfill the needs of a particular project or set of projects.

New products are generally introduced to the organization through contracts with the United States government, with the program management function responsible for the ultimate profit and loss for each contract or product. It follows that program management also has ultimate decision making authority in budget, schedule and technical concerns. The manufacturing center in Largo therefore has authority in operations, but must ultimately respond to the program managers during the decision making process.

1.3 Problem Description

Current manufacturing in Largo requires a Manufacturing Resource Planning (MRP) system to order materials and release work to the shop floor. Largo management believes that MRP and shop floor synchronization is fundamental implementing the lean transition by reducing inventory levels, cycle time variability and throughput variability. Managing to the cost, schedule and quality goals described above has not helped the Largo facility reduce variability and perform to plan.

The main goal of this thesis is to develop a method to match the scheduled MRP completions with the actual completions on the shop floor. Due to variations in production and uncertain lead times, large buffers and conservative lead time estimates are required in MRP to meet targeted due dates. This leads to the situation where production schedules are significantly different from the MRP projections. This causes a lack of synchronization between the MRP system and actual production.

The current MRP system in Largo includes large buffers (more than 30 days) between the MRP due dates and the actual contractual due dates. There are also buffers incorporated into most of the scheduled lead times. Most parts are ordered and are available to production earlier than needed. This serves as a safety stock to account for variation in production and supply chain. The buffers in the schedule also allow for production to miss MRP due dates but still satisfy contractual requirements, at the expense of higher inventories.

Cost and lead time are important to Largo's customers. While the Largo facility generally met their contractual delivery dates, the site did so in an expensive manner that could not offer short lead times.

The direct undesired results of the interactions between MRP and variable production are:

- High cost
- Long lead times
- Unpredictable lead times

- Unsynchronized production of sub-assemblies
- High levels of inventory
- Early receipts of inventory to manufacturing needs, but on time to MRP
- Lack of performance to manufacturing plan in MRP

There are also subtle secondary results of the interactions between MRP and variable production:

- Early receipts of inventory allows for early releases of materials. Some operations managers use this flexibility to release material to the floor to keep people busy during disruptions in manufacturing.
- Some lines implicitly judge performance by delivery to contract due dates, not MRP due dates. This increases the complacency associated with missing MRP dates.
- Metrics may be misleading if judged solely by MRP data or solely by operations data.

Manufacturing management is aware of these undesired results and has put emphasis on measuring the lack of synchronization between MRP and operations. They began tracking the difference between the end-item deliverables scheduled to be produced and the end-item deliverables actually produced in every week. (End-item deliverables are defined as items required by customers or other value streams. This purposefully removes sub-assemblies from the metric).

Matching the scheduled completions and actual completions will require both reducing the variability associated with production and updating the MRP system with realistic data.

2.0 Literature Review and Application to Largo

Current literature provides many mechanisms to help solve the problems at the facility in Largo. Researchers advocate moving to a just in time (JIT) system for repetitive production with moderate product variability, and imply that MRP does not work well in this environment.^{3,4}

However, there is some debate about the conclusion that MRP and JIT do not work well together. MRP and JIT can be used together, with MRP providing the mechanism for long-term scheduling and kanbans used for day-to-day inventory movement decisions.⁵ Also, since MRP and JIT share similar conceptual structures, MRP can be modified to work with each of them.⁶ Much of the integration between MRP and JIT concepts is available through software solutions.⁷ When compared with MRP, kanbans provide better inventory control system.^{8,9,10,11}

MRP tends to have issues with human interaction because most line-workers are far removed from the implementation and maintenance of the MRP database. On the other hand, kanbans tend to work well with the line-workers because they can be involved in the decision making process and can see how the system is designed to work.^{12, 13}

Variability in the system can be reduced by introducing repeatable processes.¹⁴

Companies that possess repeatable processes tend to perform better in both manufacturing metrics and business metrics.¹⁵ Recognition of the inherent variability of the system is key to reducing the effects on production.¹⁶ Some facilities have reduced variability using real-time display of production information to help management make consistent decisions.¹⁷ Another key concept in reducing variability is to focus on the constraint as described in the Theory of Constraints.^{18,19} IT systems have also evolved. MRP software has incorporated new modules to align with lean concepts and help solve these problems.^{20,21} The end state of a hybrid push-pull system using MRP and kanban pulls can produce superior performance than either system used alone.²²

Aligning management techniques and human resources to a new system will be necessary to ensure a culture change. The elements emphasized in literature include cross training, developing problem solving processes and building an effective communications infrastructure.^{23,24,25}

Current literature is clear on the mechanisms to reduce variability and on the desired future state of a process, but lacks the integration of these results into a larger system that is also undergoing change. The novel approach in this thesis is to solve the problems involved with MRP and the shop floor during a lean transition. Developing the proper feedback to MRP (and thus to the material system as a whole) will provide insight into the true gains possible on an enterprise scale.

3.0 Analysis

The analysis of the problem and solution will be considered in terms of both the physical process and the business environment.

3.1 Manufacturing Process

MRP uses lead times for suppliers and processes to determine when to order materials. The system uses a bill of materials (BOM) and lead times to work backwards from the ultimate customer demand to determine the latest date that materials must be ordered. MRP then helps build purchase orders to bring in material and shop orders to start production. MRP also allows for buffers to be in place to account for variability in the system.

Some realities of manufacturing make it difficult to perform to the MRP plan. MRP does not have an allowance for missing due dates. Any late production to the MRP plan creates a backlog and may require re-scheduling. Also, MRP does not force capacity checks on the plan and may build a plan that is not possible to achieve.

Therefore, it is critical to have accurate estimates of production capacities, lead times, variances and bills of materials to be able to perform to the plan generated by the MRP system. Uncontrolled variation in these items will cause a divergence between the reality on the shop floor and the MRP plan.

3.1.1 Variability at Largo

A good indicator of the variability at this manufacturing site is the comparison of the quantities of actual completed assemblies with the planned completed assemblies. The planned and scheduled completions for each week of the first six months of 2006 are shown in Figure 3-1. This clearly shows that the production is not following the plan, and that there is significant variability in both the planned weekly production and the actual weekly production.

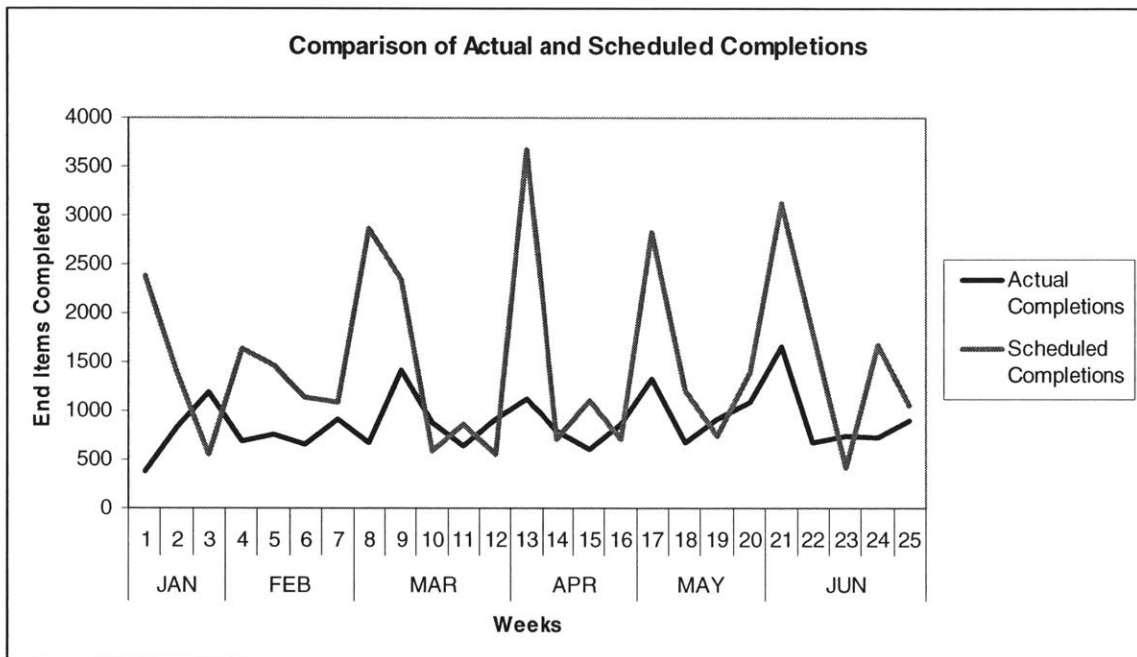


Figure 3-1 Comparison of Actual and Scheduled Completions

3.1.2 Root Cause Analysis

The variability in the actual versus the planned production may be caused by the following:

- Planned versus actual lead time inaccuracy

- Actual lead time variation
- Schedule variation
- Supplier variation
- Material availability

Comparing the actual lead times and the planned lead times for diverse part numbers will show the accuracy of the lead times in the MRP system. An effective way to show this comparison is to take the ratio of the actual lead time and the planned lead time. In this metric, if the ratio is 100% then the lead time in MRP is accurate. If the ratio is less than 100% then the lead time in MRP is too long, and if the ratio is greater than 100% then the lead time in MRP is too short. A histogram of this ratio for 14,000 shop orders representing more than 2,700 separate part numbers from this facility is shown in Figure 3-2. This figure clearly shows that the majority of the lead times in MRP do not accurately reflect the reality on the shop floor.

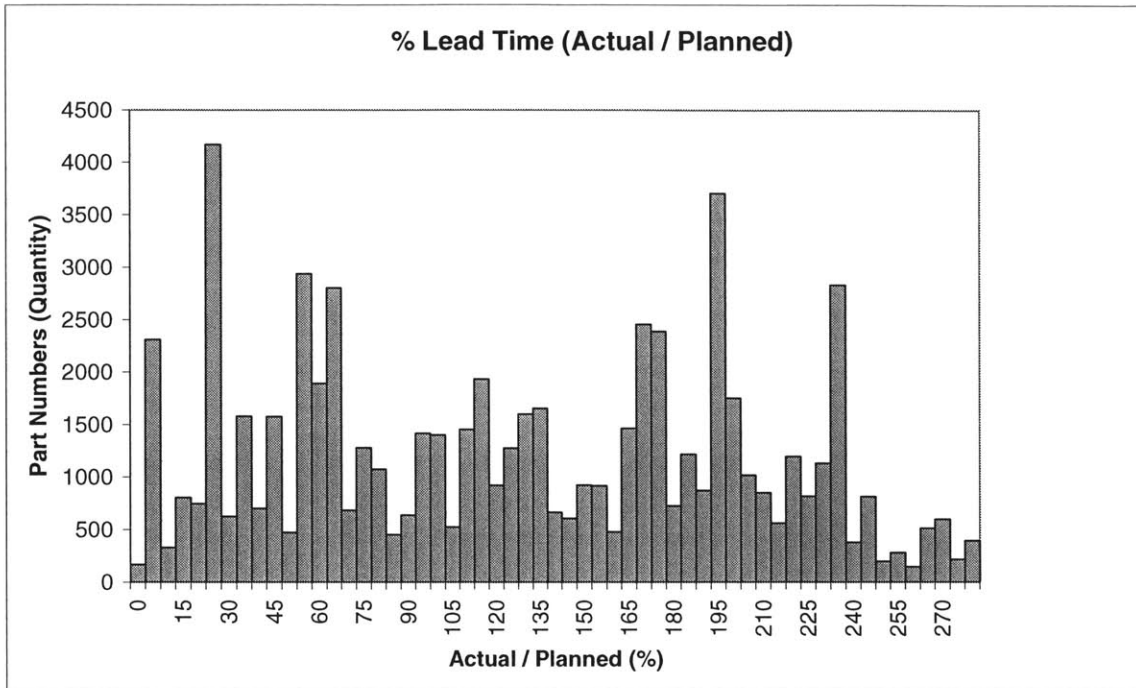


Figure 3-2 Ratio of actual to planned lead times

Lead times cannot be input accurately into MRP unless they are stable. An effective way to measure this stability is to take the ratio of the standard deviation of the actual lead time to the average actual lead time for each part. This gives us the coefficient of variation for the actual lead time, as shown in Equation 3-1.

$$C_v = \frac{\sigma}{\mu}$$

C_v : coefficient of variation

σ : standard deviation

μ : mean

Equation 3-1 Coefficient of Variation

This metric determines the percent variation from the average value, and is shown for a majority of part numbers in the facility in Figure 3-3. As shown, the coefficient of variation is generally above 30%, making it difficult for the static value of the lead time in MRP to accurately reflect the reality on the shop floor.

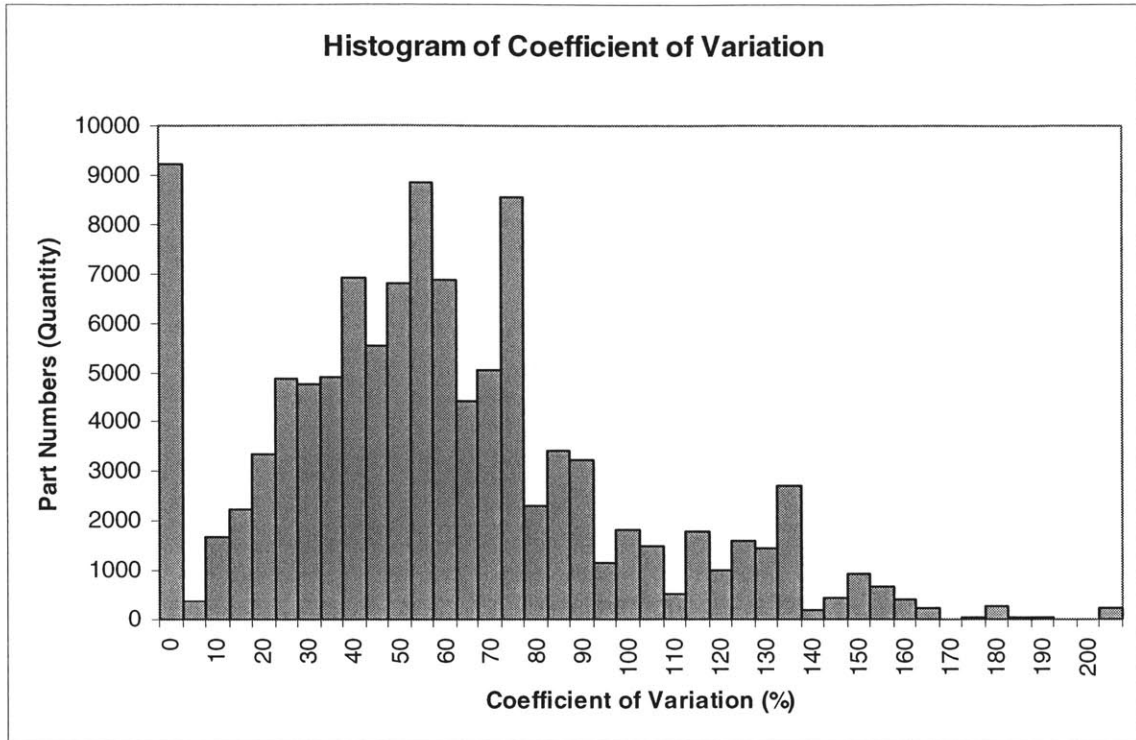


Figure 3-3 Percent Deviation of the actual lead times

Variability in the production schedule itself may be a cause of significant variability on the shop floor. Weekly delivery schedules (as shown in Figure 3-1 at the beginning of this section) show significant weekly variation in the planned deliveries. Investigation of the planning database showed that most of the variability was due to re-planning missed target dates. The planning system deteriorated in a cycle of re-planning missed deliveries and subsequent lack of performance to the new due dates. Re-planning of due dates therefore is common in the MRP database. Figure 3-4 shows the percentage of items that required re-planning in each month for the first six months of 2007.

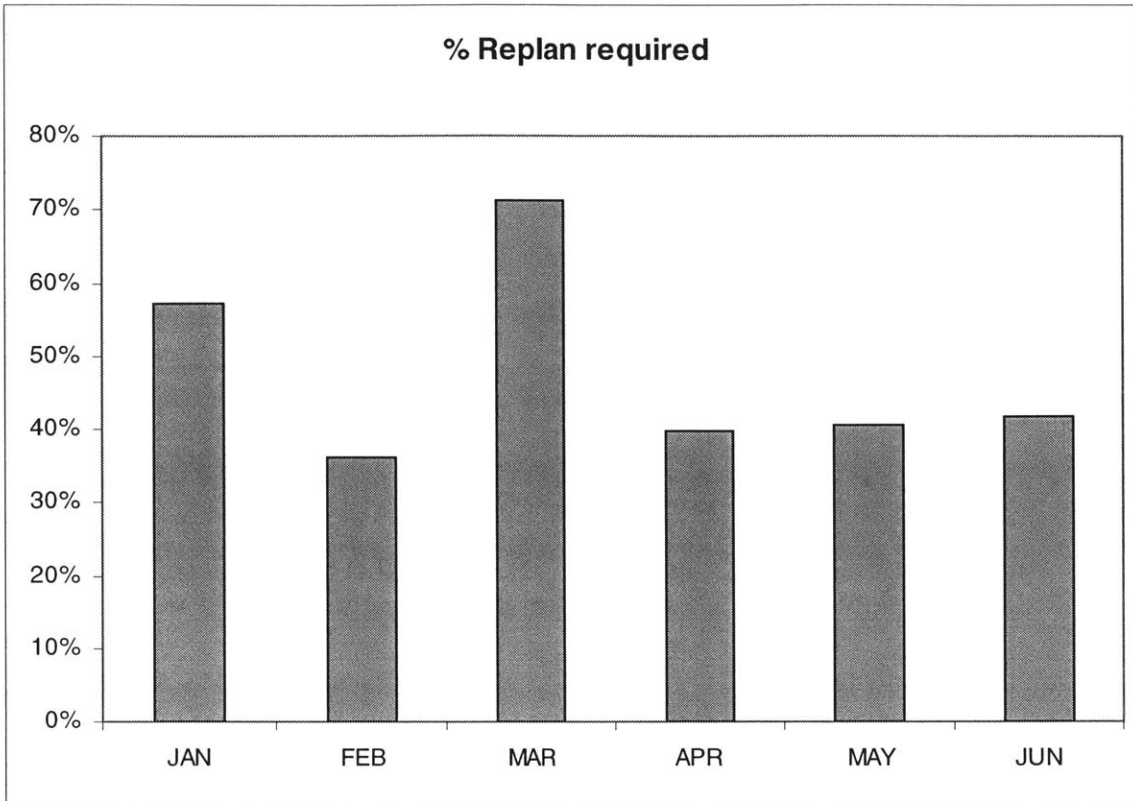


Figure 3-4 Percentage of deliveries that missed targeted due dates and required re-planning

Problems with meeting production schedules may also be caused by suppliers either not providing parts on time or providing defective parts. If a delinquent or faulty part is critical to meeting production schedules and requires immediate delivery from a supplier, the part is placed on the “red-list” of the supply chain organization. The higher the quantity of parts on the “red-list,” the more likely it is that production will not be able to make scheduled deliveries. The percentage of delivered parts on the “red-list” is shown in Figure 3-5. As shown, there are usually more than 2.5% of the parts on the “red-list,” which is more than sufficient to disrupt production.

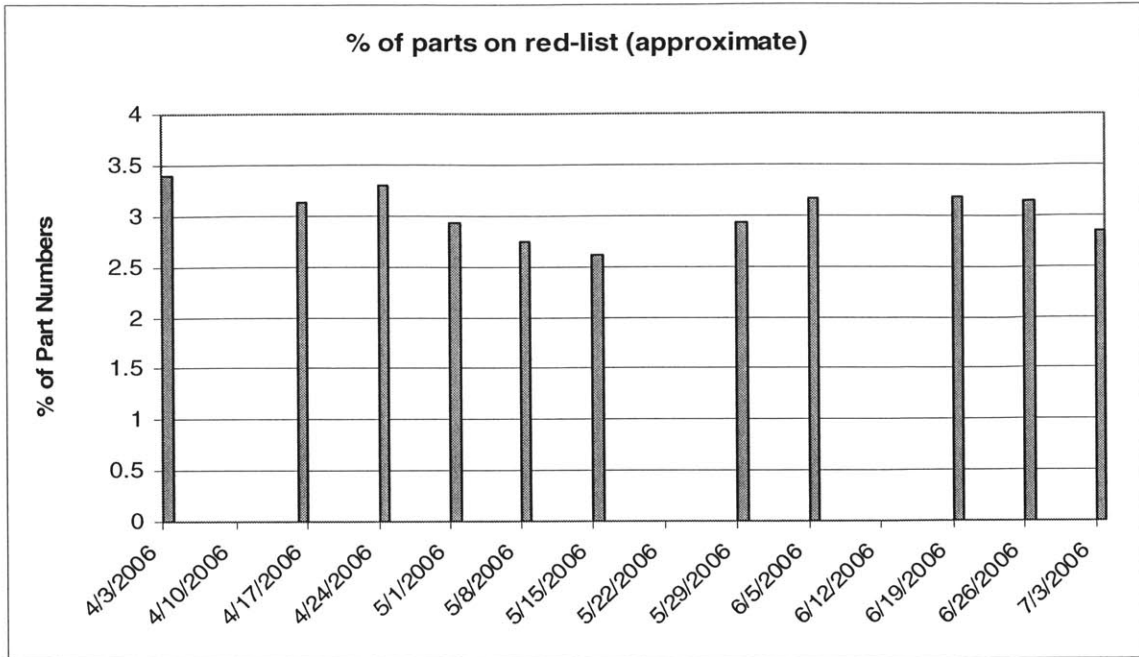


Figure 3-5 Percentage of Parts on the “red-list”

Each supplier is judged by its performance to the negotiated contract date, to the MRP due date and to their promise date. The three dates are required because the contract dates are based on the MRP dates, but MRP may change after the contracts are signed. Therefore, the supply chain organization may ask a supplier to promise to another date if the MRP date has changed significantly after contract signing. Histograms of the performance of suppliers to each of these dates are shown in Figure 3-6. These histograms show the quantity of PO lines (roughly equivalent to separate part number deliveries) and how early or late they are to the desired date. This shows, with the exception of the parts on the “red-list,” the remainder of the supply chain for Largo is stable in their delivery schedules.

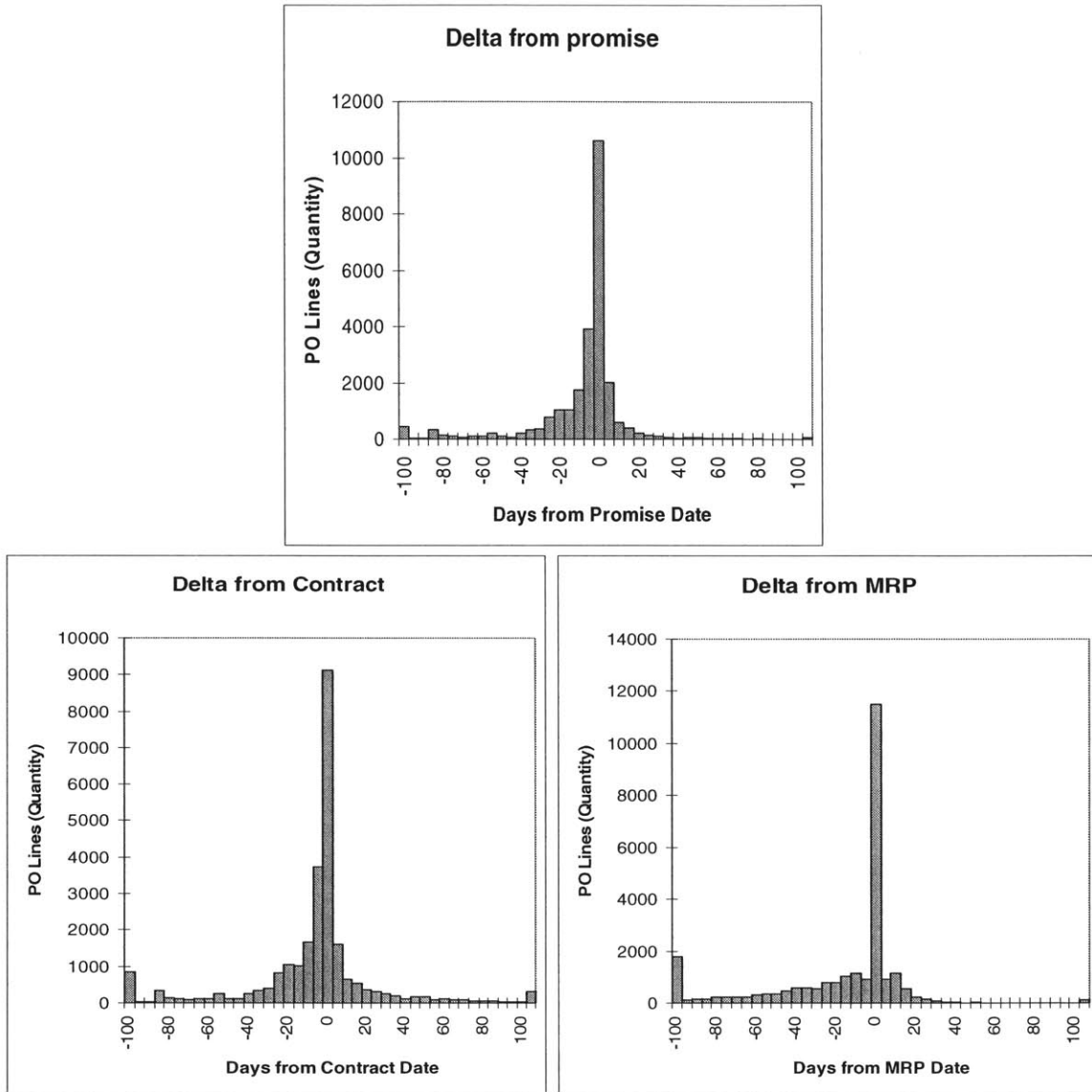


Figure 3-6 Performance of suppliers to critical dates

3.2 Business Environment

There are three important, non-quantitative aspects to the business environment that affect the ability of production to meet the plan: authority division between operations and program management, cultural attitudes, and operations metrics.

3.2.1 Authority Division

The program management teams control budget and schedule, and the operations teams control cost in the NCS organization. Given this arrangement, it is easy to deduce that the program management teams have more power in the organization than the operations teams. Many of the decisions made by program management teams are in their own self-interest, and not always in the best interest of the operations teams. These decisions may require that operations work in a sub-optimal manner, with recent examples including:

- Ordering excess inventory because revenue on some contracts may be recognized on inventory receipts
- Waiting on design-for-manufacturability fixes because the fixes weren't bid in the original contract.
- Waiting on production upgrades because the program remains profitable with the current production system.

3.2.2 Cultural Attitudes

The culture at the largo facility embraces stability in the organization. Roles and responsibilities do not change often, and rotation between functions is not common. In these roles, experience is the most important deciding factor in decision making.

These attributes have led to a system where past decisions are reinforced and the assumptions underlying those decisions are rarely revisited. The past decisions that have caused the variability in the system are not easily changed.

3.2.3 Operations Metrics

There are two major metrics that drive shop floor behavior, hours-per-unit (HPU) and CLIN on time delivery (CLIN is a term for contractually required delivery).

HPU is the accounting allocation of direct labor contribution to each manufactured item. This is tracked individually at each step in the process. If a worker is not actively engaged in working with a manufactured item, then the worker logs down-time. Workers are understandably discouraged from charging down-time. The undesired consequence of this metric is that workers try and keep busy working on manufactured items, even if those items will not soon be required by subsequent steps. Therefore, the shop floor has a tendency to build up waste as work in process as people try and keep busy.

On time delivery is important to keep credibility with customers. In order to deliver on time, buffers are put into production schedules to allow for unforeseen problems in manufacturing. Buffers are also put into sub-assembly steps and into the supply chain. For the Largo facility, there is not a consistent manner of allocating or identifying these buffers. Each buffer is decided by a negotiation between the master scheduler, the program manager and the manufacturing manager responsible for the product line. Some programs have a standard buffer, and others have buffers that are determined on a case-by-case basis. In the majority of cases, the buffers are incorporated into the MRP lead times at the inception of the program and are rarely revisited. The end effect is that the MRP schedule is loaded with enough buffer time that it is not a reasonable predictor of the necessary state of manufacturing on the shop floor. Operations leadership has

significant leeway in the day-to-day scheduling of activities on the shop floor. The undesired consequence of this activity is that it is acceptable for the actual manufacturing activity to be out of synchronization with the production schedule.

3.3 Root Cause Analysis Conclusions

The core reason that the shop floor is unable to stay synchronized to plan is the variation in shop floor performance as shown in Figure 3-2 and Figure 3-3. Therefore, the key to improving the MRP to shop floor synchronization in Largo was to improve stability in cycle times for manufactured items. Stable cycle times make it possible to update MRP with accurate data and use the MRP system to drive better decision making through the entire organization.

4.0 Process Improvement Implementation

The process improvement described here is focused on reducing actual production variation. Little's Law²⁶, shown in Equation 4-1, describes the relationship between work-in-process inventory, cycle time and production rate. This equation shows that cycle time may be stabilized by controlling both throughput and in-process inventory. Inventory will need to be controlled at every process step, with throughput being controlled at the constraint. Inventory controls are most effective when coupled with a pull system. The process improvement will therefore include a pull system, inventory controls and throughput controls.

$$I = RT$$

I: work in process inventory

R: production rate

T: Cycle time

Equation 4-1 Little's Law

In order for the improved system to work properly, visual controls and new metrics are required. Buy-in from the program management and experienced operations leaders will also be required for the new systems to function properly within the current Raytheon culture.

As mentioned in 2.0, research suggests that the Largo facility should move from an MRP based system to a JIT system using kanbans to control in-process inventory and reduce variability. MRP was used in Largo as a scheduling system that signals each process to begin production based on the dates calculated in an external database. These calculations are based on user inputs for delivery due dates and the lead times for each component. In contrast, the appropriate JIT system for the Largo scenario would be one that uses kanbans as the signaling system between stations rather than an external database of due dates. Each kanban would be associated with a particular item and the quantity of that item that is required. When the item from an upstream process is consumed by a downstream process, the item's corresponding kanban is sent back to the upstream process to signal that more production is required. The quantity of items associated with the kanban should be enough to overcome variability and production delays. In the JIT system, items will be produced at the proper rate only if they are consumed at that rate by the downstream processes. In the MRP system, items will be produced at the proper rate regardless of consumption. Therefore, kanbans and JIT

production provide mechanisms to match production to consumption and reduce the in-process inventory variability associated with the MRP system.

In order to give an indication of the magnitude of improvement on this product line, the graphs shown in this section will contain data from before the process improvement was completed. The graphs in the results discussion (Section 5.0) will contain performance after the implementation of the improvement projects.

4.1 Value Stream Description

The production line that builds a family of secure mobile radios was used as the pilot for the process improvement implementation. These radios are used by the U.S. Air Force and Army for two-way, secure communications in battlefield environments. Each type of radio uses common or similar modules, such as synthesizers, drivers, receivers, transmitters and security devices.

The modules in each type of radio are built by outside suppliers, with Raytheon assembling and aligning each of them to work together in a complex system. All the different versions of these radios have architectures similar to a desktop PC, where a chassis holds a motherboard and multiple circuit cards. Each card has a different optimized capability.

Most modules require component placement, soldering, testing and adjustment prior to being installed into a radio. These modules are built on four different production lines. The modules are then “mated” into a different housing for each radio and put through a

series of tests specific to the radio. After testing, final touch-up and inspection is performed.

4.2 Throughput controls

The first step in the process improvement was to map the process and identify the constraint. Monolithic test sets for acceptance tests and final tests were the constraint for two types of the radios, and the radio mate sequence was the constraint for the other type of radio. Although some parallel capacity was available, the most that could be regularly produced was slightly more than one unit per hour for each radio type in the system.

A system was put in place to monitor the real-time throughput and yield at the constraint. This system consisted of a connection to their quality database that tracked passes and failures at key points in the manufacturing process. Although this data has always been available in their quality database, this new system represented a change in focus for the operations management team. Computer displays were put up near each constraint to display these new real-time metrics. An example of the display is shown in Figure 4-1

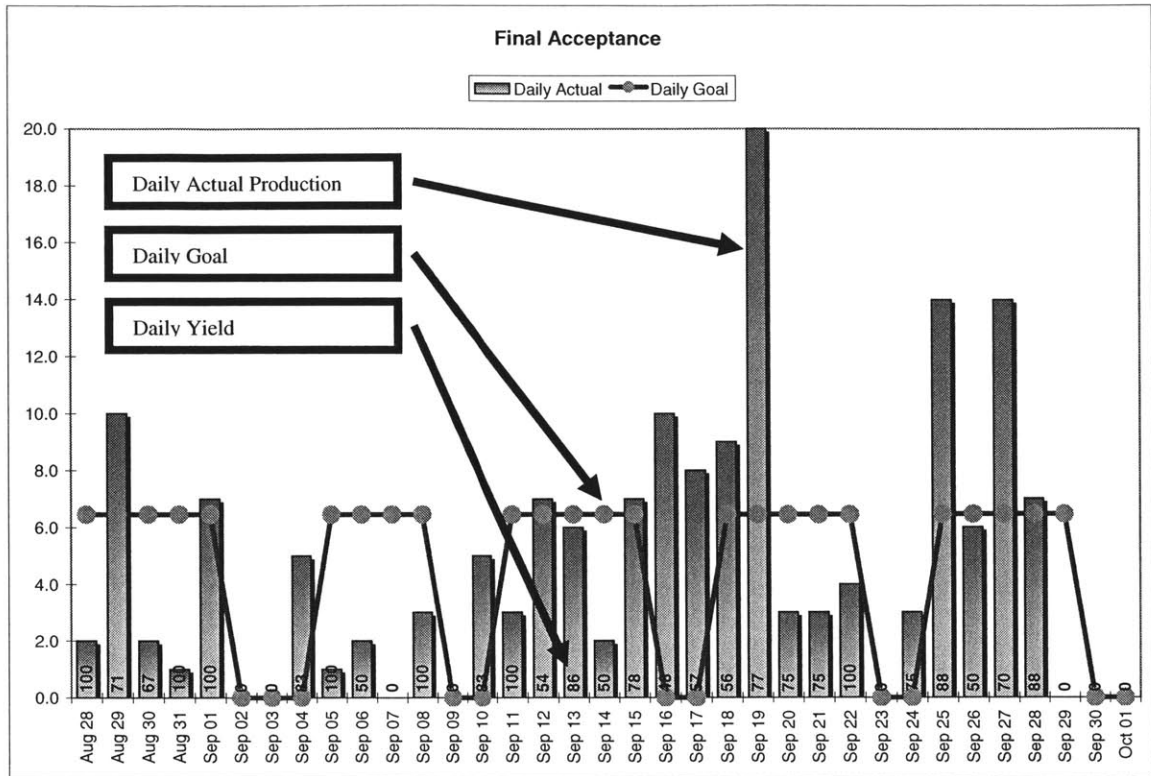


Figure 4-1 Throughput and yield display at constraint. Note that the daily yields are shown as numbers at the bottom of each bar in the graph.

As can be seen in Figure 4-1, the constraint for this radio had problems with meeting the linear throughput goals during the time period shown. Some of the problems were due to supplier issues, and others were due to operational issues. The solutions and future work associated with these issues will be discussed in the Conclusions section (section 7.0) and the Future Work section (section 6.0)

4.3 WIP Limits / Pull System

After implementing throughput monitoring, a pull system and work in-process (WIP) inventory limits were put in place.

The in-process inventory limits were instituted using kanbans. We should note that this change from the MRP system to the JIT system with kanbans requires a fundamental change in operations. Each process stage no longer receives a fixed, scheduled quantity to produce each day from MRP. It will now receive a daily goal and signals from kanbans indicating when to produce. A lack of empty kanbans is a valid reason for not meeting goals, and helps narrow down the problems to the area that was not producing at the desired rate.

The calculation for the optimal number of kanbans between production steps was developed by Toyota and is shown in Equation 4-2.^{27, 28}

$$n = \frac{d_{ave}(t_w + t_{pc})(s)}{k}$$

n: number of kanbans

d_{ave}: average daily demand

t_w: waiting time

t_{pc}: processing time per container

s: safety factor

k: container size

Equation 4-2 Optimal number of kanbans

In this production line the highest customer demand is 12 units per day, the production line runs for 18 hours per day, and the combined processing and waiting times are less than 1 hour for each step (the constraint can operate at 1 unit per hour). In order to calculate the safety factor, we give the worst-case scenario with a 100% coefficient of variation for each process step and 0.99 service level. The theoretical kanban sizes for

process steps varying from 0.1 to 1 hour in duration are shown in Figure 4-2. Even under these worst case conditions, the largest kanban size would only be one unit.

d_{ave} (per day)	$t_{pc} + t_w$ (days)	s (days)	k (qty of units)	n (qty of units)	n (whole units)
12	0.006	0.018	1	0.00	1
12	0.011	0.037	1	0.00	1
12	0.017	0.055	1	0.01	1
12	0.022	0.074	1	0.02	1
12	0.028	0.092	1	0.03	1
12	0.033	0.111	1	0.04	1
12	0.039	0.129	1	0.06	1
12	0.044	0.148	1	0.08	1
12	0.050	0.166	1	0.10	1
12	0.056	0.185	1	0.12	1

1 day = 18 hours
 Process steps vary from 0.1 to 1 hours

Figure 4-2 Calculation of theoretical kanban sizes.

However, due to the culture and human elements involved in the system, the in-process inventory limits were negotiated with the station operators and production management. The kanban sizes between most process steps ended up being a shift's worth of inventory (six units). Although the system could have theoretically tolerated less in-process inventory, these limits were still a significant improvement over the current state.

Run rules were also required to determine activities in the presence of in-process inventory limits. These rules provided a team level, prioritized checklist that governed production activities. The highest priority activities were those that helped deliver end-items to the customers, with the remaining activities those that improved the process.

The specific run rules were defined as follows:

1. Fill constraint kanbans.
2. Fill downstream kanbans.

3. Help other teams fill kanbans.
4. Do cross training.
5. Do approved process improvement projects.
6. Do safety or sorting / cleaning projects.
7. See team leader for other tasks.

These run rules helped the operators institute the pull system.

4.4 Visual Indicators

Daily meeting boards were built for each product team to help them understand the new objectives. These boards were built to provide accurate, current data in an easily understandable format to influence day-to-day decisions. Metrics displayed on these boards were daily throughput at key stations, in-process inventory levels, average cycle time, yields and action items. The data source for these metrics is the quality database, with the exception of in-process inventory at the critical processes, which is counted daily by the production team leader.

Cycle Time

The cycle time metric graph is shown in Figure 4-3. This graph has two lines, the 30 day moving average and the 30 day minimum. The moving average is the actual metric, with the 30 day minimum providing a view of how low the cycle time can be if the line is performing properly.

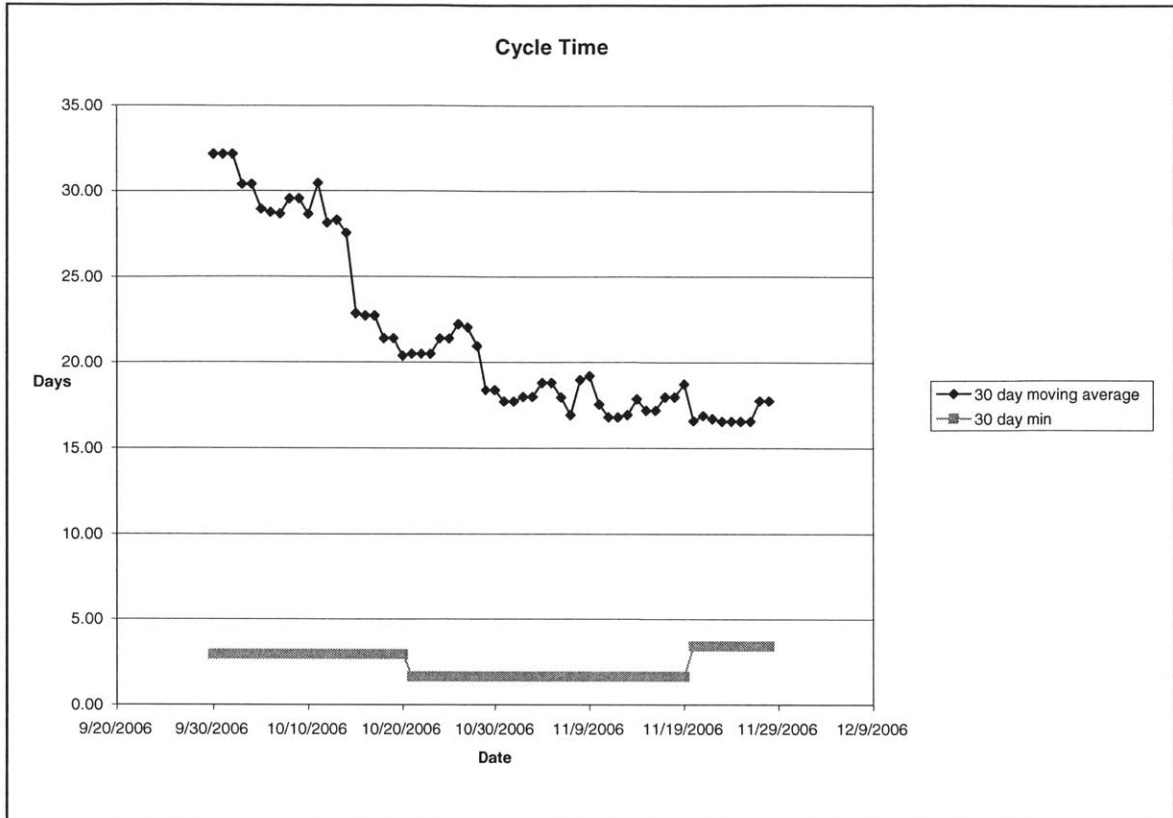


Figure 4-3 Cycle time metric

This metric is intended to drive behavior that reduces cycle time. This includes minimizing in-process inventory, minimizing non-value added time, and making process improvements.

Daily Goal, Daily Throughput and Yield

Production team leaders wished to see the daily goal, daily throughput and yield on the same graph. These were integrated together as shown in Figure 4-4. The top graph shows the daily output (bar), daily goal (line) and yield (number above bar). The bottom graph shows the cumulative output compared to the monthly total required. The line is the cumulative goal, and the bars show if the goal has been met (the actual system used

color codes, where green indicates the cumulative goal has been met, and red means the cumulative goal has not been met).

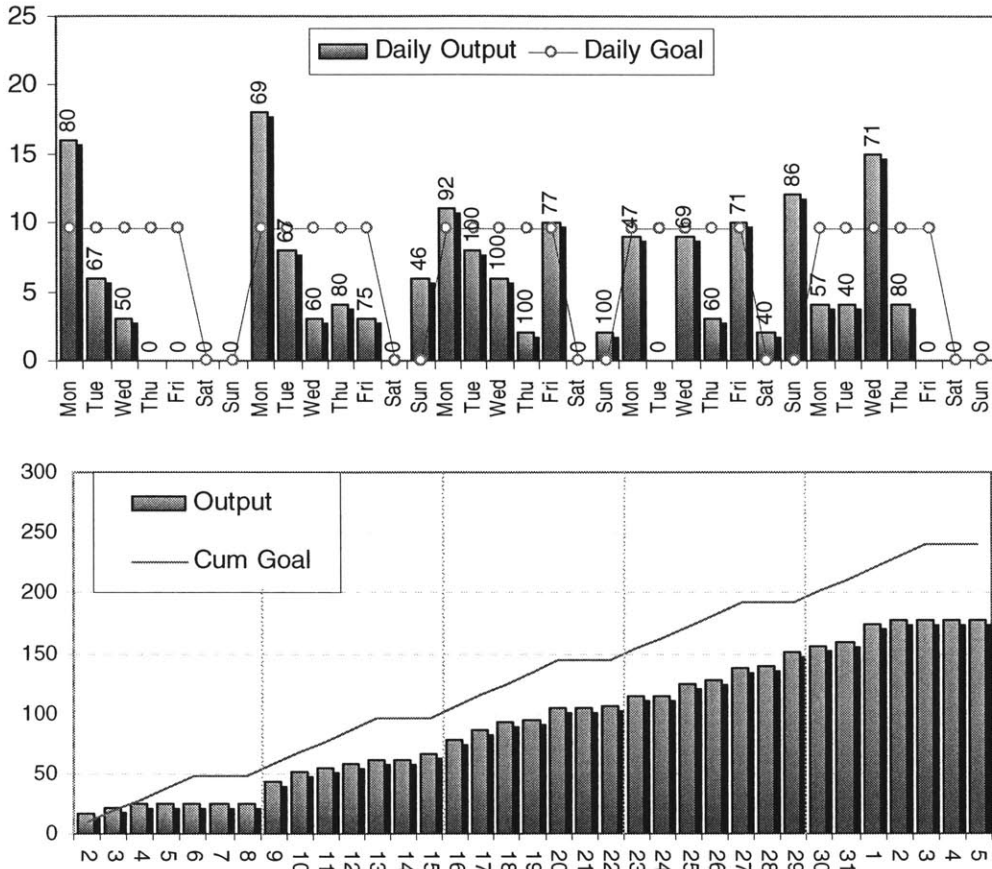


Figure 4-4 Daily goal, daily throughput and yield metrics

The daily goal, daily throughput and yield metrics are designed to drive the following behavior:

- Daily throughput should help focus on stabilizing the throughput of the system, specifically focusing on scheduling the constraint.
- Daily yield results should help show if yields are stopping the line from meeting daily goals. This should drive immediate corrective action (band-aid for the problem) and long term improvements (fix the problem)

- Cumulative results should help the line know if a consistent increase in production rate is required to remain on the monthly schedule.

Due to the erratic nature of the yields for the these product lines, it was difficult to make any meaningful yield goals. However, the production team leaders feel that any yield goal below 80% to 90% would be meaningless.

Work in Process Inventory

There are two basic inventory metrics with the same format, with an example shown in Figure 4-5. One specifically looks at the in-process inventory in front of the constraint, and the second looks at the in-process inventory on the entire line. The first is counted by the production team leader in the morning before first shift. The second is taken from quality database. The graph has three lines, one for the minimum inventory allowed, one for the maximum inventory allowed and the other for the total daily inventory.

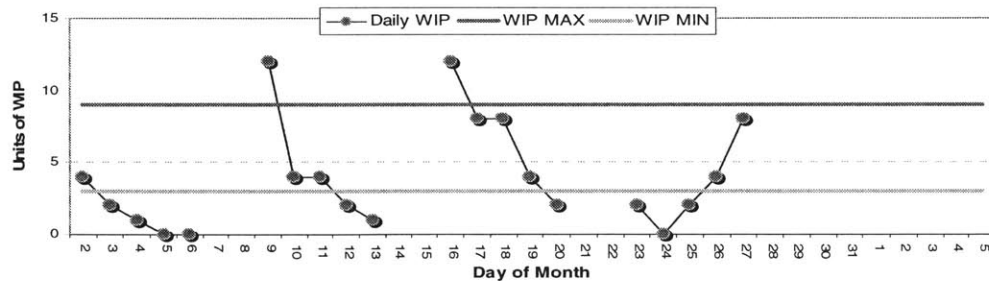


Figure 4-5 Work in process inventory metric. Note the breaks in the graph are the weekends when there were no operations and data was not collected.

This metric is intended to control the amount of in-process inventory in the system. The in-process inventory in front of the constraint is a leading indicator of the ability to meet the daily goal. This should give the production team enough advance notice to solve

minor throughput problems upstream from the constraint. The maximum and minimum lines require outside effort to change, and should only be changed when the underlying process has changed.

The combination of the cycle time, daily goal, daily throughput, yield and WIP charts were placed on the daily meeting board. An example of a board in the production room is shown in Figure 4-6



Figure 4-6 Daily meeting board

Each of these metrics is updated daily and used in the morning meeting for first shift (usually at 7:00 A.M.). These metrics are intended to help the production team make decisions for the day's activities, as described in the daily meeting agenda:

1. Did we make yesterday's goal?
2. If not, why not? Take action.
3. Will we make today's goal?
4. If not, why not? Take action.

Each action should be data driven based on the lean metrics. These actions are listed on the daily meeting board and are discussed in each daily meeting.

4.5 MRP Synchronization

Current research implies a basic five step process to adapt MRP to operate in an environment with a monitored constraint and kanban pull system:²⁹

1. Determine the constraint
2. Revise routings and lead times.
3. Compute the master schedule at the constraint.
4. Use MRP to schedule work centers.
5. Control production, measure performance.

The management team at Largo followed only the final two steps of this process before the improvements discussed in this paper were implemented. The discussion in section 4.2 regarding throughput controls shows the changes that were made to determine and manage the constraint. This section describes how to revise the routings and lead times. The key to MRP synchronization for this situation is to have the lead times and offsets in MRP match the actual behavior on the shop floor. Therefore, measured cycle times should be used to update the MRP database.

There is a translation required to take the cycle time measured on an individual piece and transform it to the lead time of a shop order that consists of multiple pieces. The first piece associated with the shop order will finish production within the cycle time. Since the pieces associated with the shop order start sequentially, subsequent pieces after the first one will come off the production line at the daily rate. The lead time for the total quantity associated with the shop order will therefore be the cycle time of the first piece, plus the time required at the production rate to finish the remaining pieces.

As an example, the lead times for the synthesizer module of one type of radio were determined as follows:

The synthesizer for the radio currently has a quantity of twelve associated with each shop order, has a measured average cycle time for each unit of four days and is built in single piece lot sizes. The synthesizers are scheduled to be produced at three a day for the radio assembly. Therefore, after releasing a shop order, it would take four days for the first item to reach the radio mate station. At a production rate of three a day, it would take an average of four additional days to produce the remaining eleven pieces on the shop order. Therefore, the lead time should be eight days for the synthesizer shop orders.

Offsets between sub-assemblies and higher-level assemblies need to be calculated for MRP as well. In some cases, the shop order for the higher-level assembly may be started before the completion of the shop order of the sub assembly. To continue with the example, the shop order for the radio may be started when the first synthesizer is available and does not have to wait until the twelfth synthesizer is finished. Therefore the radio shop order may be started four days after the synthesizer shop order is opened, and

not wait the entire eight days to finish all twelve synthesizers. The relationship between lead times and offsets is shown in Figure 4-7.

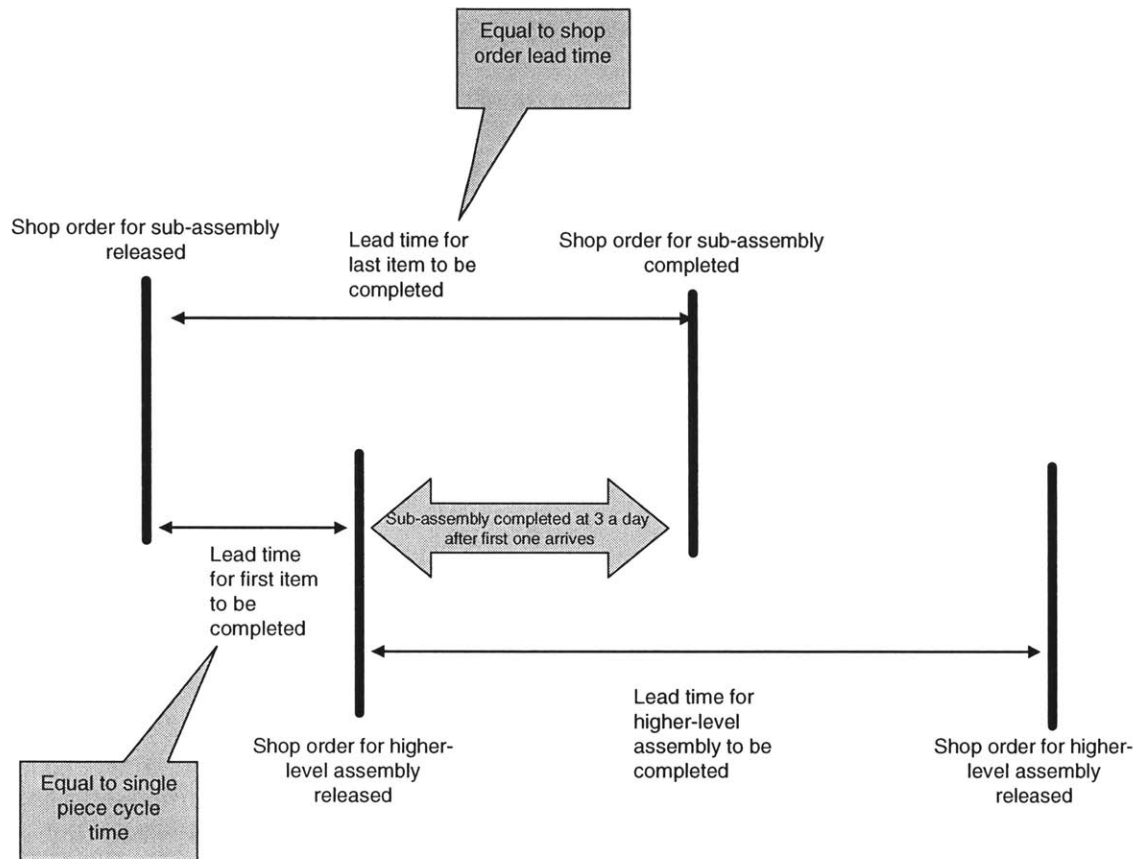


Figure 4-7 Offsets and lead time relationships between sub-assemblies and higher-level assemblies

The basic process for updating the MRP database is as follows:

1. Work continuously to decrease the shop order sizes and plan with the smaller shop order sizes. This should be done until the shop order size matches the actual production lot sizes.
2. Determine the lead time for each shop order, based on the quantity planned. This should be based on actual data of the daily rate required and the cycle time for each part.
3. Determine the offset in the bill of materials (BOM) for each item. This will plan for some overlap in each level in the BOM, such that the module shop order does not need to finish before the radio shop order is released.

4. Run a simulation to determine the effects of the changes. This is used to determine the excess inventory that our storeroom due to the long lead times for a inventory mitigation plan.
5. Gain approval of supply chain, program management, operations and material program management on the changes. The simulation should be used to communicate the impacts of the potential changes.
6. Change the lead times and bill of material offsets in MRP.

The MRP lead times and bill of material offsets should be updated when major events occur (demand changes, major improvements, etc), shop order sizes change, or after every three to four months when the actual production has diverged from what is in MRP.

4.6 Business Environment

As described in section 3.2, the important aspects of the business environment associated with this project are the authority division between operations and program management, cultural attitudes, and operations metrics.

This new system was able to stay within the authority division in the current system. The changes required no changes from the program management team.

The new operating system required a change in culture in the operations organization. New metrics and a new focus on lean operations challenged the experience-based culture. Job and process specific training and coaching were used as supplements to the Raytheon Six Sigma general training. Coaching sessions with the management teams were also used to help generate understanding and acceptance of the new system.

The efforts to change the culture were augmented by a shift in the metrics emphasis. HPU and CLIN on-time-delivery were de-emphasized and the daily meeting metrics were emphasized. This emphasis shift was designed to drive behaviors that allowed for the system to remain stable.

5.0 Process Improvement Results

The throughput controls, inventory limits / pull system, visual indicators, metrics were successful in decreasing the variability on the production line. These improvements were then fed back into MRP to give more synchronization between MRP and the actual production line.

Largo's customers benefit from the lower cost solution due to lower inventory levels and lower inventory handling costs. They also benefit from shorter lead times that allows the Largo facility to be a more agile supplier.

5.1 Manufacturing Process

5.1.1 Throughput Stabilization

Throughput controls were successful on the module lines. The display for the module constraint is shown in Figure 5-1. The throughput monitoring began on 8/28 and was successful until a supplier issue halted production on 9/20.

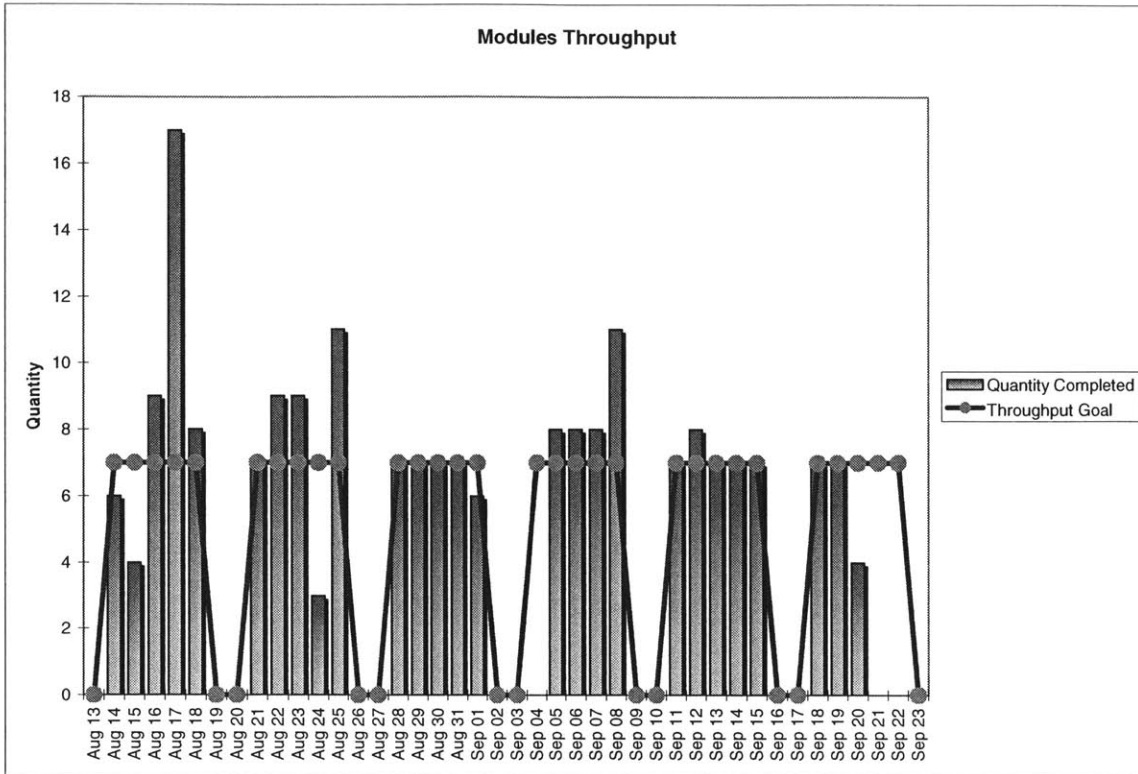


Figure 5-1 Throughput display at modules constraint. Note that the yields at this constraint were always 100% and therefore removed from the display.

From 4/1/2006 to 8/28/2006, the average throughput on the module constraint was 4.3 modules per day and the standard deviation was 4.8 modules per day. From 8/28/2006 to 9/20/2006, the average throughput was 7.6 modules per day and the standard deviation was 3.2 modules per day. The coefficient of variation went from 112% before the improvements to 42% after the improvements. This provided a much greater amount of stability for the scheduling system.

5.1.2 In-Process Inventory Reduction and Stabilization

With the pull system, inventory limits and run rules in place, the inventory on the line quickly decreased to the limit levels as shown in Figure 5-2. Each separate line on the

graph corresponds to a module (circuit card) that is used in the final radio. Along with a reduction of nearly \$3 million in inventory on the floor, this reduction helped decrease and stabilize the cycle times.

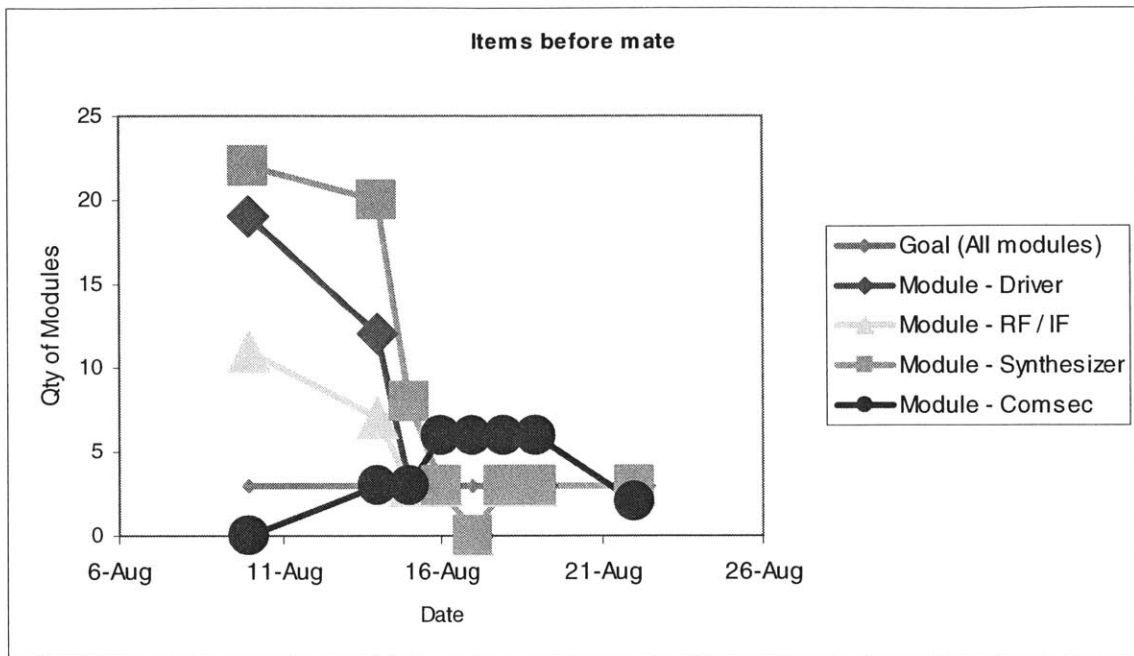


Figure 5-2 In-process inventory level reduction with inventory limits and pull systems

5.1.3 MRP Synchronization

With in-process inventory and throughput stabilized, the cycle times for the modules were shorter and more stable. We were able to implement these controls on 19 of the 22 different part numbers in the value stream. As shown in Figure 5-3, the parts that went through production systems with the improvements had significantly less variation than those that went through systems without improvements.

	With Improvements	Without Improvements
Average Deviation Percentage (stdev. / mean)	69%	123%

Figure 5-3 Comparison of cycle time deviation percentage for parts with controls and parts without controls

The shorter, stable cycle times were translated to lead times and are being put into MRP through the process outlined in section 4.5. A good indicator of MRP improvements is the stacked lead time, which indicates the time to complete both the sub-assembly and final assembly of the final product. The stacked lead time is an indicator of the total manufacturing lead time for the final product. Stacked lead times improved significantly in MRP due to the improvements of the manufacturing system, as shown in Figure 5-4. Note that the stacked lead times shown here include only the modules and radio assemblies, and not the lead times for suppliers.

	Historical Time (MDAYS)	Improved Time (MDAYS)
Stacked lead time (modules and radio)	25	16

Figure 5-4 Comparison of stacked lead time for systems before and after improvements

The full financial benefits of the shorter, stable cycle times will not be realized for a few months after implementation of the new system. Inventory in the store rooms will be moved through the system after purchase orders and contracts have been renegotiated, leading to a time when supplier deliveries will be less than the output of the system.

After this normalization occurs, the system will have less inventory on the shop floor and in the store room.

5.1.4 Results Simulation

Simulations of the current and future systems also show the benefits of the improvements. The simulated process flow for the radio production line is shown in Figure 5-5. Radios flow through a few assembly and test steps, and go through optional rework steps if failures occur at the critical tests.

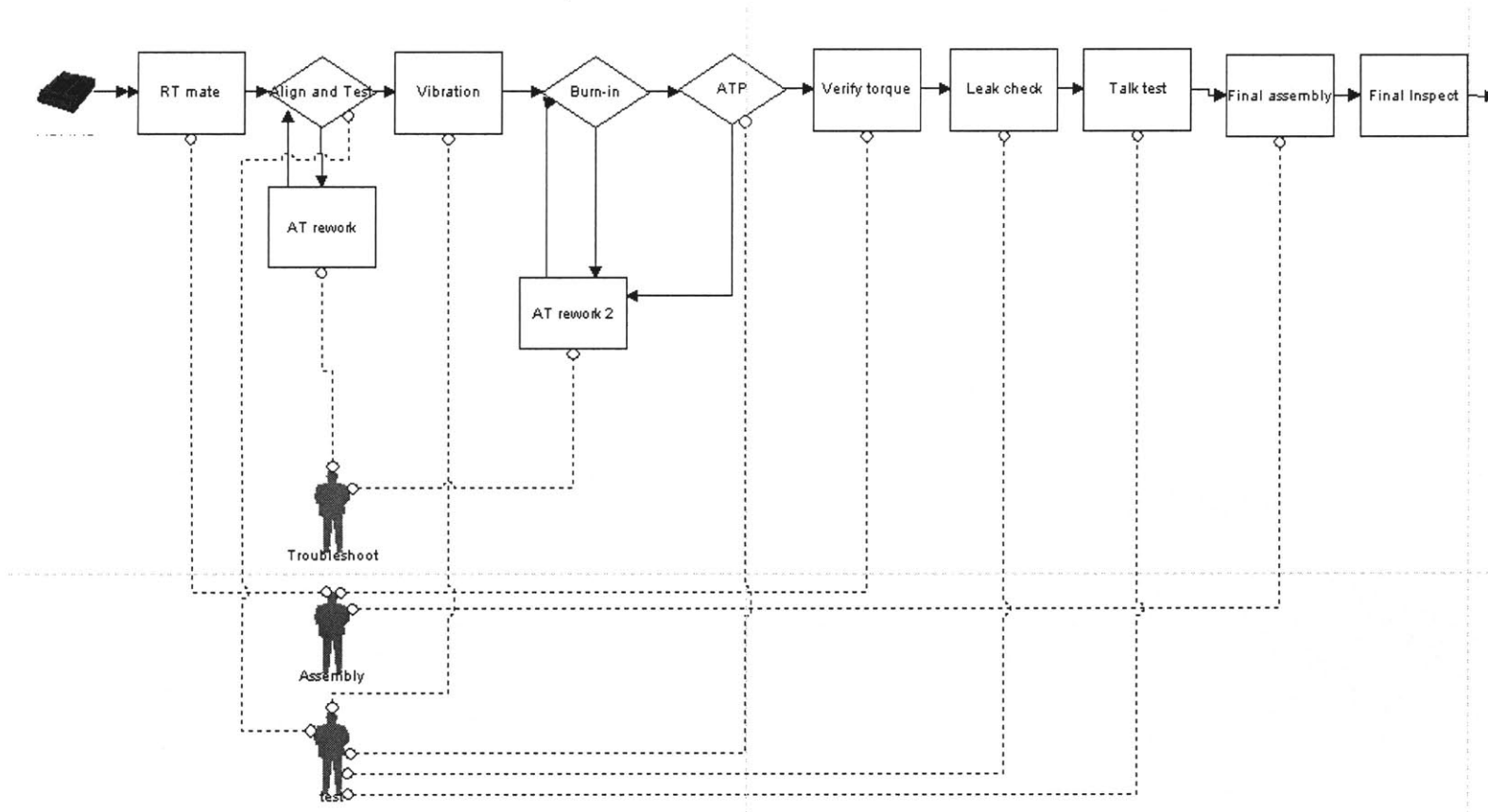


Figure 5-5 Simulation diagram for radio production line

5.1.4.1 Simulation Development

Promodel is the standard tool for simulating the operations environment for the Raytheon Six Sigma team. At a high level, this tool enables describing the process flow in terms of *entities*, *processes*, and *resources*. *Entities* are the items being processed, *processes* are the steps in the operation, and *resources* are the items required (in addition to the entities) to finish the operation.

Entities – The radio is the entity being processed in this simulation. The simulation traces the movement of this radio as it is processed through the important steps.

Important simulation parameters, such as cycle time, are tracked for each entity. Each entity also has a Boolean variable describing if it has passed through a rework loop, which allowed for different processing rules for reworked and first pass items.

Processes – The operations performed on the radio were split into 12 major processing steps. These steps were identified as logical breakpoints in the process flow, where inventory tended to build up between processes and where a sequence of work was completed on a single unit before moving to the next unit. These steps are:

- Receiver / Transmitter (RT) Mate – mating all modules into an radio chassis.
- Align and Test – tuning radio characteristics to ensure that the collection of modules together will meet specifications. Failure occurs when the radios cannot be easily brought into tolerance ranges.

- Vibration Test – vibrating of the radios to ensure the unit will meet customer requirements. None of the entities in the actual system failed this test during the period under observation; therefore no failure path was required in the simulation.
- Burn-in – heating and cooling of the radio to remove infantile failures and ensure the unit will meet customer requirements.
- Acceptance Test Procedure (ATP) – testing of each of the key customer requirements.
- Verify Torque – ensuring that all the systems had front and back covers properly mounted and attaching final buttons, knobs and stickers.
- Leak Check – checking the seal of the radio unit. None of the entities in the actual system failed this test during the period under observation; therefore no failure path was required in the simulation.
- Talk test – ensuring that the audio quality of the radio is sufficient. The operator is allowed to adjust the radio to fix any talk test problem; therefore none of the entities in the actual system failed this test during the period under observation, and no failure path was required in the simulation.
- Final assembly – attaching final serial number plates and performing a paint touch-up.
- Final inspect – ensuring that all the documentation is properly completed for sell off to the customer.
- Acceptance test (AT) rework – fixing the failures that come from the Align and Test process.
- AT rwork 2 – fixing the failures from ATP and Burn-in processes.

Processes were grouped as either test, assembly, rework or inspection operations. Test operations had two outputs (one for pass and one for fail). Assembly, rework and inspection operations had only one output (no failures came from those process steps).

Each process allowed for the description of the following parameters:

- Input queue size
- Output queue size
- Travel time to next step
- Process time mean
- Process time variance
- Process availability
- Batch Size
- Yield (test only)
- Special logic (such as different processing time or yields for first-pass entities vs. reworked entities)

Resources – The operations steps required personnel resources to complete each task.

Although labor union negotiations had established numerous job classifications, from an operations standpoint the classifications could be mapped into assembly, rework or test jobs. These resources could be assigned to work on multiple process steps. The process step could not be completed unless there was an entity waiting for the process step and a resource was available to operate the process.

Each resource allowed for the description of the following parameters

- Resource pool quantity
- Resource quantity required for each step in the process
- Resource availability (shift and break description)
- Alternate resource capability (for example, rework resources could do assembly processes if required)
- Process step prioritization

Various sources of data from the production system were used to populate parameters for the entities, processes and resources. The process parameters were developed using the Raytheon quality database, MRP database, time studies and interviews. Fortunately, the operations team had worked to optimize each process step (and not the system as a whole), which gave us reasonably accurate and useful data for each of these steps. The resource parameters were developed by the first-line supervisors and their knowledge of the personnel resource pools.

Desired Outputs – The key information required from this simulation is the cycle time for each entity. The stability of this parameter is important for establishing a system that can be synchronized effectively to MRP. In addition to this primary output, the simulation also provided useful information with regards to staffing levels, effects of yields and rework loop interactions.

5.1.4.2 Simulation Results

This simulation was intended to help understand the operational parameters that are causing the large variation and cycle times observed in the production line. The cycle time outputs of the simulation model closely matched the actual cycle time data from the system (a formal description of the simulation validation is given in Appendix A – Simulation Verification).

The simulation shows the difference in cycle time average and variability with the proposed process improvements. Differences between the two simulation states are shown in Figure 5-6.

Current State	Future State
WIP between steps is unlimited.	WIP limits in place.
No prioritization of processing steps	Processing steps prioritized: 1st - Constraint 2nd - Rework 3rd - Steps closest to end of line 4th - All other steps
Entire incoming queue on a step processed before moving to another processing step	Single piece processing based on priority
Personnel assigned to particular steps	Personnel cross-trained to work on any required step
Personnel capabilities not balanced across shifts	Personnel capabilities balanced across shifts

Figure 5-6 Changes between current state and future state in the simulation

A histogram of the cycle time for the future state and the current state are shown in

Figure 5-7. There are two main conclusions that can be made quickly from the data:

1. The future state has identifiable spikes that correspond to physical causes and can be used for planning lead times in MRP.
2. The future state has lower average cycle time and lower variation.

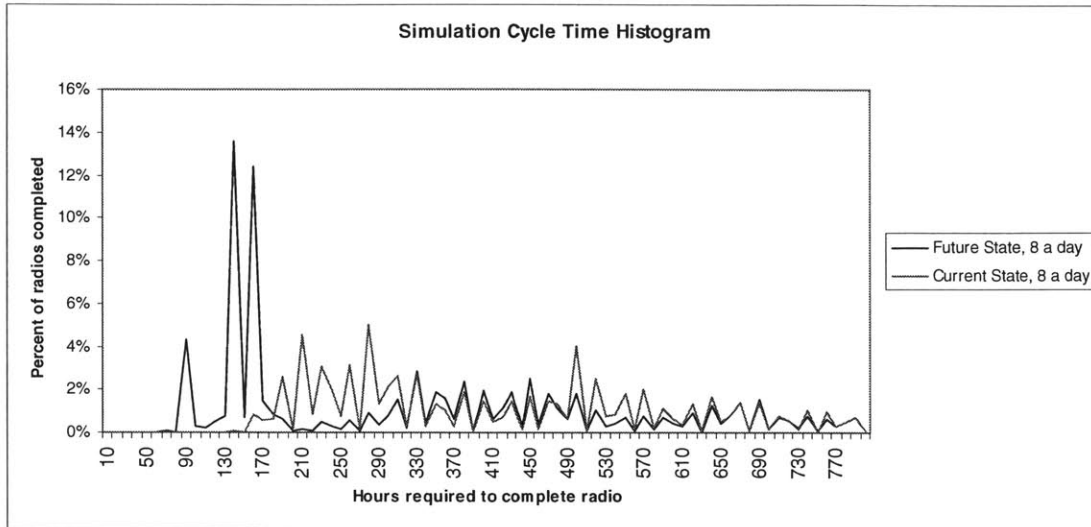


Figure 5-7 Histogram of simulation results for future state and current state cycle times

The differences between the future state and the current state highlight important operational characteristics. The first three main spikes of radio completions in the future state occur at the following times:

- 90 hours – equivalent to processing time with very little queue waiting
- 138 hours – equivalent to processing time with waiting over a 48 hour weekend
- 160 hours – equivalent to processing time, waiting over a 48 hour weekend and going through the failure / repair cycle once.

The lack of these spikes in the current state shows that the waiting time in queue is the dominant factor in the cycle time for the current system. The main difference between the two systems is the elimination of the majority of queue waiting in the future state. Note that these spikes in the cycle time histogram are useful for planning purposes. They provide a set of target times of how long radios should remain in the system.

The current production system is scheduled to go from a rate of eight radios per day to twelve radios per day. A simulation at these higher throughput rates shows the same basic characteristics, as shown in Figure 5-8. In this scenario, the future state continues to perform well at the higher rate, but the current state performs poorly.

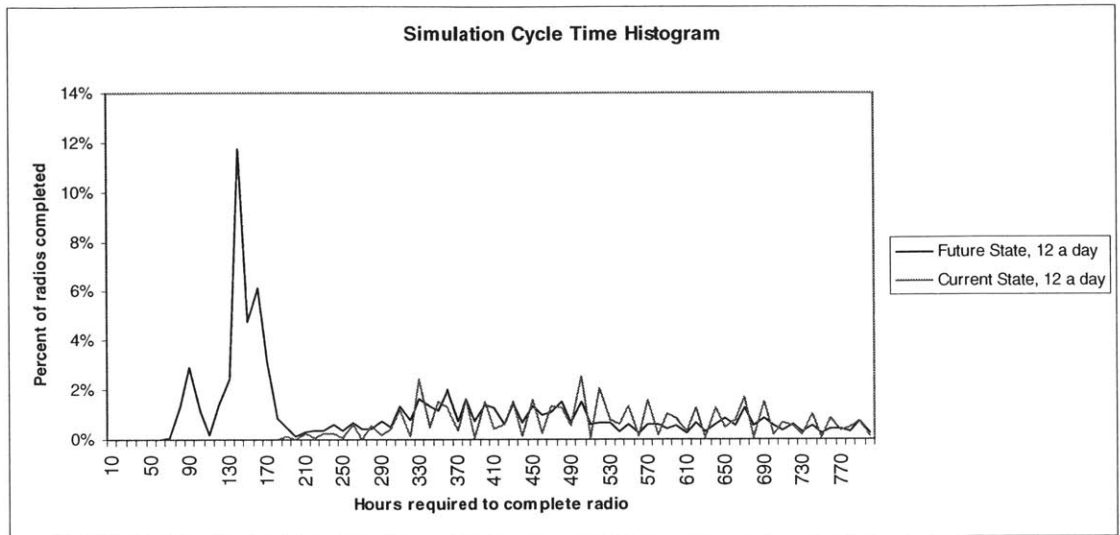


Figure 5-8 Histogram of simulation results at higher throughput rates

The key results of the simulation study are shown in Figure 5-9. This clearly shows that the future state performs better in both the average and variance of the cycle time, especially at the higher rates. This stability will allow for more effective planning and MRP synchronization.

	Current State		Future state	
	8 radios a day	12 radios a day	8 radios a day	12 radios a day
Average Lead Time	26 days	46 days	21 days	21 days
Stdev Lead Time	18 days	36 days	18 days	19 days

Figure 5-9 Results of simulation study

5.2 Business Environment

As described in section 3.2, the important aspects of the business environment associated with this project are the authority division between operations and program management, cultural attitudes, and operations metrics.

The new system of operations did not require a change in the authority division for the current system. It only required communication with the program management office. Fortunately, the Raytheon Six Sigma group already put mechanisms in place for communication of process improvement projects across NCS.

Changing the cultural attitudes was more difficult than working with the authority division. The experience-based culture did not readily accept new operating conditions, nor did the culture accept the questioning of the pervasive batch-and-queue mentality. The seeds for cultural change were laid by the Raytheon Six Sigma group, with training specifically aimed at educating the workforce around lean principles. This training was used as a common denominator for discussions of the actual implementation of the new mechanisms. The culture change will remain an ongoing effort, even after the systems were in place and functioning.

The cultural attitude disconnect was readily apparent in the conflict between the new metrics on the daily meeting board and the traditional metrics of HPU and CLIN on-time-delivery. The new operation system removed the capability to flood the floor with inventory to help with the HPU metric, and stopped moving large batches of in-process

inventory through the system to meet scheduled delivery dates. The new system required a lower headcount with more versatile workers to keep the HPU metric low, and required consistent throughput to meet scheduled delivery dates. Both of these behaviors were new and met with a desire to return to the traditional way of meeting the HPU and CLIN on-time-delivery metrics.

As with any change to a business environment, there were unintended consequences with the changes implemented for this study. The manufacturing environment in Largo (and the Radio Value Stream in particular) was dealing with three additional basic issues beyond MRP synchronization: staffing issues with too many hourly workers, yield issues due to a lack of engineering design for manufacturability, and supplier quality issues due to a lack of good communication in the supply chain. This project did not solve any of these problems and increased the pressure on the operations management.

This led some members of the management team to declare that the lean initiatives are counter-productive and to withdraw their support of the facility wide lean initiatives. The site executive was surprised to hear that the longevity of the implemented solution was in danger due to these pressures and their interactions with the other problems in the facility.

Fortunately, these unintended consequences have been recognized and are being worked by all levels of management in the facility. The need for synchronization to MRP and the operational excellence it requires is driving additional change in this facility.

Management realization and significant action on these barriers (independent of this study) are signs of the positive cultural transformation taking place in Largo.

6.0 Future Work

Lean improvements in the Largo facility are fostering a continuous improvement atmosphere. In staying with that philosophy, the study team is aware of important future work that will help continue solving problems.

6.1 Manufacturing Process

The most important next step, of course, is to take the concepts learned during the pilot program and implement them across the remaining programs in the site. The stabilization of in-process inventory and throughput would have significant positive effects on the manufacturing process.

In the process of developing the system described in this paper, additional related process improvements were identified. Therefore, in addition to wide-scale implementation of the ideas in this paper, the process improvement team could also be pursuing the following opportunities:

- Attacking other sources of variability
- Finding a good way to reduce excess in-process inventory without disrupting staffing
- Finding a good way to operate when the buffers hit the inventory limits
- Understanding how do deal with supplier variability
- Understanding how to react when daily goals are not met

Going through the process, it was clear that more factors exist that affect the variability of the system. While the variability reduction shown in Figure 5-3 is impressive, there is still a significant amount of variability remaining in the system. There are obvious gains to be made through improving yields and the turn-around-time of design for manufacturing fixes on existing product lines.

During the pilot implementation, significant amounts of in-process inventory needed to be worked through the system to lower the total inventory on the line. Workers whose jobs involve early-process steps (such as kitting, first assembly, inspection, etc.) were put under stress as the need for their efforts evaporated for a few weeks. This effect will occur on every product line as this system is implemented, and will cause a significant staffing problem for the leadership team. This issue needs to be addressed before a site-wide implementation is reasonable.

There are many situations where a certain process step must stop due to inventory limits. In the Largo facility, these stopped processes cause downtime for operators. The management team for this facility needs to identify a robust process for dealing with short-term disruptions to the labor requirements.

Many times inventory limits were hit due to supplier problems. The management team in this facility needs to understand the impacts of supplier issues in the new system and develop a process for mitigating those effects.

Many of the day-to-day problems of the manufacturing line are highlighted in the daily throughput metric and inventory limits in the new system. Management needs to find a way to energize the workforce around these new metrics and align the workforce's incentives to achieve the goals around these metrics.

New metrics have been put in place on the shop floor, but the shop-floor leadership does not have robust procedures in place to help meet the goals of these new metrics. New processes and procedures need to be developed to help the leadership respond to the new pressures in a structured manner. This guidance will be critical in helping minimize unforeseen, undesirable effects.

6.2 Business Environment

As with any major change initiative, there are problems to be solved and roadblocks to be removed in order to achieve true success. Although the systems put in place have achieved the technical goals, the management team needs to continue evolving the culture to support lean initiatives.

Many of the day-to-day problems of the manufacturing line are highlighted in the daily throughput metric and inventory limits in the new system. Management needs to find a way to energize the workforce around these new metrics and align the workforce's incentives to achieve the goals around these metrics. Misalignment of metrics, rewards and punishments is a classic management problem that exists at the Largo site.

The culture at the Largo site needs to transform to focus on waste reduction. Most employees at the site understand that the bureaucracy and current operating practice produce large amounts of waste. However, the culture is not in place to have these same people attack and remove the waste.

Hierarchy is important at the Largo site. In line with this importance, many workers are worried about their position and reputation in the hierarchy. This influences many people to filter the current situation such that the good results are readily visible and the poor results are easily forgotten. The management team then makes sub-optimal decisions due to lack of an honest appraisal of the current state. The management team needs to recognize this cultural phenomenon to allow a more open discussion of the current state.

7.0 Conclusions

This implementation of this project has revolved around two major ideas:

- Lean manufacturing tools provide necessary stability in a manufacturing system
- This stability can be used to update a classically used MRP system to improve site-wide performance and to make the lean transition easier.

These findings are important for facilities like the Raytheon plant in Largo, where traditional batch and queue and MRP systems are used. The mechanisms given above can be used during the transition from the traditional mass-production system and a more efficient lean system.

The more efficient lean system also helped Largo satisfy customer demands. Shorter lead times and lower costs are now competitive weapons in the area where the new systems were implemented.

This work also shows the importance of implementing the systems within the cultural framework of the facility. Metrics are especially important in this activity, especially using the metrics while understanding the desired effects and being willing to adapt when the undesired effects occur.

Appendix A – Simulation Verification

The most straightforward way to statistically verify this model is to compare a histogram of the actual data and the simulated data of the cycle time. The most flexible method for this comparison is the Kolmogorov-Smirnov Test³⁰.

This test has two distinct advantages:

- It does not require that the actual data follow any particular distribution.
- It compares the shape of each distribution and not just the summary statistics (mean, standard deviation) of the distributions.

The test works in this basic fashion:

1. Develop a cumulative distribution function (CDF) of the actual data.
2. Develop a CDF of the simulation data.
3. Plot the two together
4. Determine the maximum vertical distance between the two plots. This is known as the d-value.
5. Make sure the d-value is less than the accepted value.

For samples > 35 , the critical value at the 5% level is approximately $1.36/\text{SQRT}(n)$, where $n = \text{sample size}$. For this simulation, $n = 253$ data points and the critical value is approximately 8.6%.

The CDF of the simulation results and actual data are graphed together in Figure A.0-1:

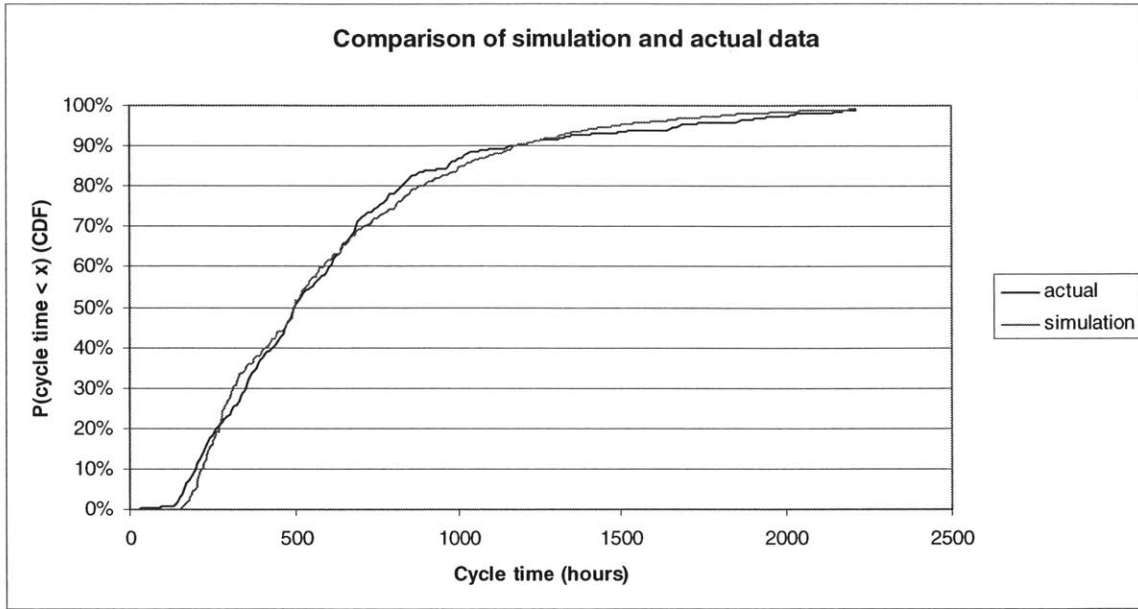


Figure A.0-1 CDF comparison of actual and simulated data

The calculated the d-value for these two distributions is 6.6%. Therefore, the results of this simulation should be considered valid to the desired level of accuracy.

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