Implementing Pull Production within an Aerospace Assembly Operation

By

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Bachelor of Science in Mechanical Engineering, Duke University (2001)

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

Master of Business Administration and
Master of Science in Mechanical Engineering

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Abstract

This thesis presents a detailed analysis of lean implementation at Hamilton Sundstrand, a global supplier of technologically advanced aerospace and industrial products. The main objective of the internship was to convert from a push system, where orders are expedited and scheduled at multiple points in the process, to a pull system driven by a bin size or finished goods supermarket. Some of the key issues addressed include system design for highly variable processes, experimentation with various forms of Kanban, and the use of value stream mapping as a change management tool.

This thesis is divided into two separate projects, both directly related to pull production. The first assignment was to redesign a subassembly process to improve fulfillment at the downstream assembly operation. Broader in scope, the second task involved implementation of a constant work-in-process scheduling system or CONWIP. Each project was designed and executed through value stream mapping and continuous improvement. The following discussion focuses on both strategic and tactical challenges of lean transformation because analysis and implementation were equally important throughout the internship.

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Chapter 1: Introduction

Similar to recent Leaders for Manufacturing internships at United Technologies, this project was motivated by an “Operations Transformation” initiative being driven throughout the company. Conceived of in 2003 as a means to sustain competitiveness in a global environment, Operations Transformation (OT) is aimed at three objectives: to modify the infrastructure, to rationalize the manufacturing scope, and to improve the operations execution.¹ OT is complemented by UTC’s lean manufacturing program called ACE for Achieving Competitive Excellence. While these initiatives encompass activities throughout the entire supply chain, this internship focused primarily on internal production processes.

This thesis presents a detailed analysis of lean implementation at Hamilton Sundstrand’s Mechanical Engine Systems division and is a continuation of a previous LFM internship.² Hamilton Sundstrand is a subsidiary of UTC. The main focus of the project was to convert from a push system, where orders are expedited and scheduled at multiple points in the process, to a pull system driven by a bin size or finished goods supermarket. Some of the key issues addressed are optimization of a subassembly, challenges of implementing a Kanban system, and the benefits of Constant Work-in-Process (CONWIP) versus traditional Kanban.

1.1 United Technologies

George David, Chairman and CEO of United Technologies (UTC), sums up his company as follows “UTC is a global technology corporation with a long history of pioneering innovation in aerospace, aviation, helicopter design, climate control, elevator design and hydrogen fuel cells.”³ More specifically, UTC is a diversified company that consists of six independent business units:

- Carrier heating and air conditioning systems
- Hamilton Sundstrand aerospace and industrial systems
- Otis elevators and escalators
- Pratt & Whitney aircraft engines
- Sikorsky helicopters
- UTC Fire & Security protection services

In addition to these businesses, UTC engages in fuel cell production and development for commercial, transportation, and space applications through their UTC Power division. They also operate a central Research Center to facilitate the development of new technologies and processes.

² Previous intern was Kevin McKenney, LFM Class of 2005.
³ http://www.utc.com/profile/index.htm
In total, UTC’s various businesses generated $42.7B in revenue (2005) with a workforce of 220,000 employees worldwide. Figure 1 shows the revenue broken down by division in 2004. UTC has approximately 4,000 locations in 62 countries and has been named “Most Admired” aerospace company by Fortune magazine for the past five years in a row.4

Figure 1. UTC Revenue by Business, 2004 Annual Report

1.2 Hamilton Sundstrand

Hamilton Sundstrand, headquartered in Windsor Locks, Connecticut, is among the largest global suppliers of technologically advanced aerospace and industrial products. The company designs and manufactures aerospace systems for commercial, regional, corporate and military aircraft, and is a major supplier for international space programs. Industrial products, consisting of four separate companies, serve industries ranging from hydrocarbon, chemical and food processing to construction and mining.5

Hamilton Sundstrand was formed with the acquisition of the Sundstrand Corporation in 1999 and subsequent merger with UTC’s legacy division Hamilton Standard. These two companies have a rich history dating back to 1905 and 1919 respectively with an impressive list of innovations including the first controllable-pitch propeller and the first electronic engine control system. Today, Hamilton Sundstrand generates $4.4B in sales and employs roughly 16,000 employees worldwide.6

Figure 2 shows the Hamilton Sundstrand organizational chart. This internship took place in the Mechanical Engine Systems division (MES), a subdivision of the Engine and Control Systems business unit (E&CS). E&CS acts as a single source systems provider

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4 http://www.utc.com/profile/facts/index.htm
5 http://www.hamiltonsundstrandcorp.com/hsc/details/0,4482,CLI1_DIV22_ETI6080,00.html
6 UTC 2005 Annual Report
for jet engine manufacturers such as Pratt & Whitney and General Electric. Their products include engine controls, fuel pumps, gearboxes, start systems, and gas turbine accessories.

![Hamilton Sundstrand Business Unit Organizational Chart](image)

**Figure 2.** Hamilton Sundstrand Business Unit Organizational Chart

### 1.3 Mechanical Engine Systems

The Mechanical Engine Systems division (MES) is an assembly and test operation. They buy nearly all of their components from suppliers, both external and internal. MES assembles a wide variety of products, most of which can be categorized into three groups: Jet Fuel Controls (JFCs), Gas Turbine Accessories (GTAs), and Starters. Of the three, JFCs account for the majority of sales and are the most labor intensive assemblies. A sample of MES’s product categories is shown in Figure 3.

At the time of the internship, MES employed roughly 45 hourly technicians, 20 salaried engineers, and 5 managers. Total revenue for 2005 was approximately $50M, a 15% increase from the year prior. The hourly work force is unionized and has remained relatively constant despite the recent sales growth.
1.4 MES Operational Challenges

As a high-mix, low-volume operation, MES faces several challenges to implementing a lean production system. This section describes some of the key characteristics identified at the beginning of the project as items to consider for project selection and subsequent system design.

1.4.1 Product Variety

With more than 60 different products and annual demand around 3000 units, MES is most definitely a high-mix, low-volume operation. Demand across product lines ranges from two or three up to 350 units per year with an average around 50. To make matters more difficult, the various products have little commonality in parts or design. This broad assortment of parts, almost all of which are purchased, leads to a complex and somewhat disintegrated supply chain.

1.4.2 Product Complexity

As illustrated in Figure 3, jet fuel controls are complicated, labor-intensive assemblies. This product complexity leads to long and highly variable processing times. Assembly times range from 1 to 40 hours per unit, with an average of roughly 8 hours. With standard deviation greater than 50% of the mean in most cases, process variability is considered high by industry standards. Factors that influence variation include part shortages, operator experience, and rework. Variation data is presented in further detail in Chapter 4.

After assembly, the units are tested using large fuel rigs that reproduce engine operating conditions. Test times are very similar to assembly times, averaging about 10 hours a
unit. More importantly, test yield is relatively low, around 85% across all products. The units that fail require extensive rework which leads to high variation in overall cycle time. In addition to the labor required for teardown and repair, there is added time for engineering disposition and administrative processing.

1.4.3 Part Shortages

"Part shortages" was the most frequent response from the technicians when asked to identify the organization’s most critical issue. A part shortage simply means that the builder does not have all the parts he needs to assemble a unit. There are various reasons explaining these shortages including late supplier delivery, poor inventory management, single-sourcing, or quality non-conformances. As a result, the technicians are often forced to “build short” or out of sequence to accommodate the missing part. Building short is not officially tracked as a metric but based on conversations with various technicians at least 8 out of 10 units are built short.

1.4.4 Cross Training

The highly complex nature of MES’s products requires experienced technicians to assemble and test them. Because of the variety in products, each model has its own certification requirement. For a technician to become certified, he or she must be trained and then successfully build a predetermined number of units, usually around five. This process is both time consuming and requires two resources in place of one. In a high pressure, production driven environment, training is often a low priority. With over 60 models and 45 technicians, each of which is certified on an average of two or three products, training becomes a major constraint. This lack of cross-training forces shop floor supervisors to micromanage both the production schedule and resource allocation.

1.4.5 Scheduling

At the time of the internship, all production was scheduled using a centralized Materials Resource Planning (MRP) system. This system is used throughout Hamilton Sundstrand and is very entrenched in all facets of the company from the supply chain to manufacturing to the customer. Under MRP, parts are ordered in advance based on a demand forecast. While MES’s demand is relatively firm six months out, the long component lead times and subsequent processing times cause orders to fall off schedule which results in frequent expediting. By eliminating MRP and implementing pull production, MES should in theory be able to limit the expediting and improve on-time delivery to the customer.

While there is potential for improvement in all of the challenges listed above, scheduling was chosen as the focus of this internship mainly because it was the most manageable given the time and scope of the project. The other reason for focusing on pull production was the recent request from a key customer to establish a finished goods supermarket. As will be discussed throughout Chapter 4, the key deliverable for this internship was to put the physical elements in place to execute pull production. Kevin McKenney’s thesis
(LFM class of 2005), provides more detailed information and analysis on the other challenges listed above, specifically part shortages and cross training.7

1.5 Approach – Value Stream Mapping

Although the internship objective was straightforward from the beginning, it was critical to develop a comprehensive understanding of the operation before making any changes. In addition to the traditional methods of research, observation, and informal interviews, Value Stream Mapping (VSM) was used as both a learning device and to establish a framework for managing change. Value stream mapping is a tool that helps to see and understand the flow of material and information as a product makes its way through the value stream. A value stream is defined as all the actions (both value added and non-value added) currently required to bring a product through the main flows essential to every product: (1) the production flow from raw material into the arms of the customer, and (2) the design flow from concept to launch.8 For this internship, the value stream was limited to actions inside the plant, from receiving to shipping, but the main concept still applied.

For the projects discussed in this thesis, VSM was taken a step further by scheduling an all day event to physically walk the process and interview key stakeholders. These events were attended by a team of five or six key members including the author, the operations manager, the manufacturing manager, and two or three engineers. Following the walk-around, the team gathered to construct both current and future state maps. In some cases, more than one future state map was created to represent both short and long term process improvements. These VSM events served as valuable kick-off meetings and more importantly created a collective future state vision which could then be turned into a project plan. After the event, weekly team meetings were held to track progress and discuss results until the future states were realized.

1.6 Overview of Chapters

This thesis began with an introduction to United Technologies, Hamilton Sundstrand, and the Mechanical Engine Systems Division, with an emphasis on the operational challenges faced by MES. Chapters 2 and 3 will discuss the first of two projects completed during the internship which was to design and implement a two-bin Kanban system for the EMID subassembly process. Chapter 4 focuses on the development of a CONWIP system driven by a finished goods supermarket. Finally, Chapter 5 addresses some of the cultural issues associated with change management and presents the lessons learned from both projects.

8 Rother, Mike, and John Shook, Learning to See, Brookline: The Lean Enterprise Institute, 2003.
Chapter 2: Defining the EMID Project

Before making any changes that would impact the entire operation, the team decided to first begin on a smaller scale with an “offline” subassembly process. The intent was to develop a robust process for implementing a pull system that could be used across the organization. The other objective, aside from impacting the bottom line, was to demonstrate the potential for process improvement through lean concepts.

2.1 EMID Background

Most units built by MES require several electromechanical interface devices, generically referred to as EMIDs. Simply put, an EMID is any part that has wires attached. While some EMIDs are purchased ready for installation, most are received with unfinished wires that need to be cut to a specified length and pinned before being assembled into the final unit. This procedure was at one time completed “on the job” as part of the final assembly sequence, but was recently pulled out as a subassembly to be done “offline”. The motivation for moving the process offline was to reduce labor cost by paying a less skilled technician to complete the relatively simple job of cutting wires and attaching contact pins.

The EMID pinning procedure was chosen for analysis due to the lack of an existing process. As a subassembly, EMID production was subject to the bullwhip effect leading to major fluctuations in order fulfillment. As will be discussed in further detail in the next section, EMIDs were essentially pinned in the order they were received from the supply base, independent of what was needed downstream. Another reason for selecting this process was the potential for significant inventory reduction considering the high-dollar value of EMIDs. The cost of a single EMID ranged from $400 to $5000, while the average inventory held was around $800,000, accounting for nearly 10% of MES’s total inventory.

2.2 Current State

As mentioned in section 1.5, the process improvement team began the EMID project by conducting a Value Stream Mapping event in early July. This section describes the EMID process as it occurred near the beginning of the internship which will be referred to as the “current” state. The following sub-sections provide some detail to accompany the Current State Map shown in Figure 4.

Suppliers: There are roughly a dozen different EMID suppliers, ranging from very small mom and pop operations to large electronics companies. Most of the supply base is located within the United States, so orders are delivered via truck 1-2 times weekly with lead times ranging from 5-20 business days.

---

Issue Work Order: The parts go through a central receiving department before they are delivered to MES. Upon MES’s receipt of the EMID, the material handler will release a work order in the MRP system and deliver a batch of parts to the processing queue. Batch size is set arbitrarily at the discretion of the material handler and varies considerably, (ranges from 1 to 15). The material handler typically performs this task independent of the downstream demand and is therefore “pushing” the parts through the system. The work order is now technically live, so cycle time is measured from this point on. This process takes 5-10 minutes.

Assemble: This step is where most of the value added labor takes place. The EMID wires are measured, cut, and pinned according to specifications. One full-time and one part-time technician are dedicated to this task and support all MES production. Work orders are processed according to an informal FIFO system which is often rearranged by the shop floor supervisor or other builders who are in need of a specific EMID. Large batches that contain six or more units are fairly common and, as will be discussed later on, lead to system inefficiencies. A typical work order of 4-6 units takes roughly 1.5 hours to complete.

Inspect: After the EMIDs are cut and pinned, they are hand delivered to an inspector who then verifies that the part conforms to the drawing specifications. The order in which units are inspected is at the discretion of the inspector without a formal prioritization process. EMIDs are considered low priority and are often set aside for jet fuel controls or other completed assemblies. This process takes 10-15 minutes.

Close Work Order: After inspection, the EMIDs are hand delivered back to the material handler. The material handler will close the work order in the MRP system and deliver the EMIDs to the final assembly part racks. The work order is now considered complete thereby ending the cycle time. This process takes 5-10 minutes.

Customer: Because this is a subassembly, final assembly is considered the “customer”. Final assembly is divided into several mixed-model lines with various part racks as will be discussed further in Chapter 3. There is a major imbalance in EMID inventory throughout these part racks to the point where some models contain a 6 month supply while others are starving. This imbalance is largely a result of the “push” nature of the process and clearly demonstrates the need for a just-in-time (JIT) system.
2.3 Project Goals

One of the beneficial features of VSM is establishing a reference point. The current state map allows the team to easily identify the major issues with the process, which can then be used to determine key objectives for the project. After evaluating the current process, the team identified the following key goals:

- Reduce time in queue before the cutting and pinning operation
- Balance inventory to eliminate starvation at final assembly
- Consolidate processes where possible to reduce the overall footprint

To achieve these goals, the plan was to design and implement a pull system using Kanban as defined by the future state.
2.4 Future State

With the project goals in mind, the team constructed a Future State Map. This map, which serves as both a vision for success and a project management tool, was created after collecting and evaluating data associated with the current process. The Future State map for the EMID process is shown in Figure 5.

In comparing Figures 4 and 5, the transition from current state to future state requires the following major changes:

1) Implement a Kanban system to drive EMID production
2) Reduce and fix work order quantities according to demand
3) Train the EMID technician to issue work orders
4) Integrate the supply base into the system

Additional changes include the establishment of a clear and disciplined FIFO lane and moving the EMID assembly area closer to the material handler. This move reduced EMID travel distance significantly and more importantly consolidated raw material into one location, improving overall visual management.

Figure 5. Future State Map of EMID Process
2.5 Transformation Phases

While traditional VSM events typically produce one future state with all desired changes, the EMID process improvement was carried out in two phases to allow for adjustments, and to give the technicians time to adapt to the new system.

Phase I incorporated most of the major changes including the introduction of Kanban and fixed bin sizing. After demonstrating success with the new system, Phase II further improved the system by consolidating operations and integrating the suppliers. The development and execution of both phases will be discussed in detail in Chapter 3.

2.6 Chapter Summary

This chapter introduces the EMID project and presents the process as it was at the beginning of the internship. Several issues were identified as part of the value stream mapping event that need to be resolved. The next chapter will provide the analysis substantiating the changes planned for the future state and also discuss some of the challenges of implementation.
Chapter 3: Achieving the EMID Future State

Pointing out process inefficiencies and constructing a future state map, in a conference room, with a team of supervisors and engineers, is easy. Executing the plan in a resource and time constrained environment, where shipping the product is the number one priority, is much more difficult. This chapter will provide some analysis for changing the EMID process. It also presents the preliminary results of the just-in-time system.

3.1 Selecting a Kanban

There are several mechanisms to choose from in selecting a pull signal or Kanban. Some examples of Kanban include a card, an open space, a line, or a light. The team decided to use an empty parts bin as the indicator mainly because a two-bin replenishment system was already in place downstream. The following paragraph provides a detailed description of the existing two bin system. A second reason for selecting a bin rather than a card is better traceability. As will be discussed in Chapter 4, cards can be easily lost or misplaced. An informational photograph, shown in Figure 6, was attached to the bottom of each bin to provide a visual reference.

![Figure 6. A Sample Card attached to EMID Kanban Bin](image)

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3.2 Two-Bin Replenishment System

The final destination for an EMID prior to being assembled into a jet fuel control is a plastic bin. These bins are stored on racks that contain all of the components necessary to build a JFC. The racks are arranged by operation sequence and each part has two dedicated storage bins. The front bin is used as the primary stock, while the back is intended as a buffer. The idea is to consume parts from the front bin until it is empty, at which point the bins are swapped so that the back bin is now empty. The empty back bin serves as a visual indicator for the material handler to replenish the supply. This system works well for simple items like screws and seals that require no preprocessing, but because of the long lead time described above, it was not used for EMIDs.

The goal for the future state was to use this two-bin system for EMIDs such that an empty back bin on the parts rack is the signal to process an EMID order. The material handler would then pick up the empty bin and deliver it to the EMID FIFO lane for processing and replenishment. The second bin served as a buffer so that final assembly would have parts while the empty bin was being replenished.

3.3 Bin Sizing

Each EMID has a different assembly time depending on the number of wires and has a different consumption rate downstream depending on the JFC production rate. With over 60 different types of EMIDs that support dozens of products, selecting a universal bin size was not a feasible solution. To achieve a functional JIT system, an individual bin size would be required for each EMID type according to demand and cycle time. The methodology for calculating bin size is discussed in the following sections.

3.3.1 One Piece Flow

While lean principles would suggest one piece flow as the optimal solution, a bin size of one is not practical in this case due to the time to process each work order. Every work order is processed electronically through the MRP system. Therefore, time is required to input information into the computer. This is done both at the beginning and end of the EMID cycle as previously illustrated in the current state map (Figure 4). There is also a time savings associated with measuring and cutting the wires in batches. According to the EMID technician, the benefit of scale levels off with batches of four and higher. Hence, from an operational perspective, the optimal bin size should be somewhere between one and four.

3.3.2 Demand Analysis

EMID demand data is generated by a forecast one year out. Generally speaking, orders are firm six months out and slightly variable thereafter. Figure 7 plots cumulative percentage of demand by part number, similar to an 80/20 curve. This curve was used to filter out the low volume EMIDs that should not be included in the two bin system. These items are typically sold as spare parts or used in development hardware. It was
determined that any EMID with average monthly demand less than or equal to two would not be included in the new process. Of the 57 part numbers, 39 were to be included in the two bin system, which accounted for 97% of the annual EMID demand.

![Diagram showing forecasted EMID demand by part number.](image)

**Figure 7.** Forecasted EMID Demand by Part Number

### 3.3.3 Cycle Time Analysis

Cycle time is measured from when the EMID work order is issued in the MRP system to the time it is closed, just before delivery to final assembly. The average cycle time is 11.7 working days, with a standard deviation of 13.7 days. Figure 8 shows a histogram of cycle time for all 39 high volume EMIDs. Five of the 39 have an average cycle time of greater than 28 working days, or 5.5 weeks. This is an astoundingly large number considering the actual processing time or "touch time" is less than two hours for a typical work order. The great majority of time is spent in queue just prior to the cutting and pinning operation, as illustrated in Figure 4.

The extremely long wait time is due to the current practice of pushing work orders as EMIDs are received rather than when they are needed. It is also due in part to the frequent rearranging of the queue when orders are expedited. These push and expedite practices lead to inflated and highly variable cycle times.
3.3.4 Sizing Alternatives

The following demand based bin sizing methodologies were considered as options for the new JIT system.

1) Maximum weekly demand: Sets the bin size equal to the maximum weekly demand for a particular part number, using a one year forecast.

2) Average weekly demand with buffer: Sets the bin size equal to the average weekly demand plus one standard deviation.

Starvation at final assembly was a major concern. Therefore larger bin sizes were favored because they provided a larger buffer. The tradeoff was that larger bin sizes also led to longer cycle times, higher inventory, and added variability. Both options represented a major reduction in bin size over the current process, but the maximum demand alternative was chosen for the JIT system as the more conservative approach.

In selecting this method, it was assumed that EMID cycle time would be reduced to less than one week. Under the two-bin system, the downstream operation would have one week’s worth of safety stock in a second bin while the first bin cycles through the EMID process, thus allowing at most one week for replenishment. This was a bold assumption considering the current cycle time for the average EMID was more than two weeks (11.7
working days). By restricting the number of orders in queue, cycle time was expected to drop substantially. A load versus capacity analysis was done to verify this assumption.

### 3.4 Load/Capacity Analysis

Each EMID has a standard assembly time ranging from 15 minutes to 1.5 hrs. While the standard times are not always met, there was no actual data available so the standards were used for this analysis. Monthly load was calculated for each EMID and then totaled to determine overall shop load as shown below in Figure 9.

![Figure 9. Forecasted EMID Load Hrs vs. Capacity](image)

At the time of the analysis, there was one full-time technician dedicated to assembling EMIDs as shown by the dotted line above. The OD column represents EMIDs that were overdue or behind schedule. The large amount of overdue is evidence that one person is clearly not enough, especially during the peak months such as September and October. A second technician would have to be dedicated on an as needed basis to keep up with the heavy load during peak production. If not, the WIP queue will begin to grow and the replenishment time will increase beyond the one week threshold, leading to EMID starvation downstream at final assembly.

To keep this scenario from happening, a maximum of two shelves worth of bins was mandated for the assembly FIFO lane. Each shelf contained approximately one day’s work. Therefore the WIP queue could never go beyond two day’s work. Anytime the FIFO lane filled beyond the top two shelves, a flag was to be raised signaling the need for
a second EMID assembler. The primary EMID technician was responsible for monitoring the line and raising the flag when needed. This policy had to be strictly enforced to keep the JIT replenishment system functioning properly.

### 3.5 Results

The Kanban system was implemented at the end of July and data was collected to measure impact through the end of the internship in December. The data is summarized in Table 1, and discussed further in the following sections.

<table>
<thead>
<tr>
<th>Description</th>
<th>Old Process</th>
<th>New Process</th>
</tr>
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<tbody>
<tr>
<td>Description</td>
<td>• Push system</td>
<td>• Pull system</td>
</tr>
<tr>
<td></td>
<td>• Large, variable bin sizes</td>
<td>• Small, fixed bin sizes</td>
</tr>
<tr>
<td></td>
<td>• No visual mgt.</td>
<td>• Consolidated, easily mgd.</td>
</tr>
<tr>
<td>Cycle Time</td>
<td>μ = 11.7 days</td>
<td>μ = 4.4 days</td>
</tr>
<tr>
<td></td>
<td>σ = 13.7 days</td>
<td>σ = 3.1 days</td>
</tr>
<tr>
<td>Inv. WIP</td>
<td>$180K (3 weeks)</td>
<td>$30K (1-2 days)</td>
</tr>
<tr>
<td>Inv. Total</td>
<td>$730K</td>
<td>$715K</td>
</tr>
</tbody>
</table>

Table 1. Impact Summary of EMID Process Change

#### 3.5.1 Cycle Time

As expected, cycle time reduced drastically from 11.7 days to 4.4 days. Most of this was accomplished by converting from push to pull and limiting the WIP queue to two days worth of orders. While improving cycle time did not directly result in cost savings, it was a prerequisite for a functional replenishment system. Figure 10 shows average cycle time before and after implementation of the two bin system for all 39 EMIDs.
3.5.2 Inventory

The most significant impact of the newly implemented pull system was the improvement in inventory management. While there was no quantitative data available, starvation at final assembly was identified by both technicians and management as the key problem with the current EMID process. With the two-bin Kanban system in place, starvation at final assembly was essentially eliminated. During the four months following implementation, there were two incidents of EMID shortages, and both were due to a miscommunication between MES and the central receiving department, an issue that was eventually straightened out.

While the primary goal for the project was to balance the finished goods inventory and eliminate starvation at final assembly, it was clear that there was an opportunity for significant cost savings through reduction in raw material inventory. This reduction would only be realized if JIT was integrated into the supply chain. Without changing the ordering policy, the EMIDs would continue to flow in from the suppliers at the same rate as before; therefore any reduction in WIP would result in an increase in raw material inventory. This scenario is exactly what happened as shown in Figure 11.
After demonstrating the potential savings to the management team, it was decided to integrate the suppliers into the new JIT system as part of the second phase of the project. Towards the end of the internship, in November, the ordering policies were changed with most of the suppliers to implement an electronic Kanban through the MRP system. However, the effectiveness of these changes depended largely on the adequacy of the MRP system and coordination with the purchasing organization. The anticipated inventory reduction was not yet realized at the conclusion of the internship.

![EMID Inventory Balance](image)

**Figure 11. EMID Inventory Balance**

### 3.5.3 Visual Management

An additional benefit to the project that cannot be quantified is the consolidation of operations and inventory into one central area. Under the original setup, raw material inventory was scattered throughout the shop floor and not accessible to anyone except the material handler. A simple inventory inquiry could take up to 15 minutes just to go through each aisle and check the multiple EMID locations. Under the new system, all of the raw materials were consolidated and arranged onto two racks immediately adjacent to the EMID assembly area. In addition to reducing the EMID travel distance by 250 ft, the raw material inventory was now clearly labeled and easily visible to the supervisors which allowed them to manage the supply more closely. Figure 12 is a photograph of the EMID area after the process change. The two racks on the left contain all of the raw
material while the rack on the right holds works orders to be processed arranged as a FIFO lane. The empty chair is where the EMID technician cuts and pins each order.

Figure 12. EMID Work Area after Process Improvement

3.6 Chapter Summary

This chapter presents the analysis, implementation, and results of the EMID project as defined in Chapter 2. As mentioned previously, this project was planned as a lead-in to the larger issue of implementing pull production across the organization. The next chapter will discuss the design and transition to a supermarket driven system for MES’s primary production schedule.
Chapter 4: Implementing CONWIP

After demonstrating significant improvement with the EMID process, the focus of the internship shifted to the initial objective of revamping MES’s existing scheduling system. As discussed briefly in 1.4.5, Hamilton Sundstrand uses MRP extensively throughout all organizations. The MRP system has been used for many years and is essential to managing the growing supply chain. A pull system is designed to limit the role of MRP as it pertains to scheduling internal production, not to eliminate MRP altogether. The goal for this project was simple: design and implement a production process driven by a supermarket size rather than a customer due date.

4.1 Background

The supermarket idea came from one of MES’s major customers. The customer requested that MES maintain a finished goods inventory of a predetermined size from which they could “shop”. If MES were to agree to such a system, they would need to demonstrate their ability to maintain the supermarket size for an extended period of time. The management team realized the only way to achieve this goal was to establish a just-in-time (JIT) system via pull production, similar to the new EMID system.

Value stream mapping was again used to kick off the process. Although the team had a somewhat predetermined vision of the future state, the VSM event proved useful in understanding the existing process.

4.2 Current State

Figure 13 shows the current state of MES’s generic manufacturing process. Some units require extra steps such as kitting, but most products follow the path exactly as shown. Excluding receiving and shipping, the process consists of five basic steps: Assembly, Inspect, Test, Process, and Final inspect. As highlighted in yellow, Assembly and Test are by far the most labor intensive and highly variable processes. The other three steps are relatively consistent and only constitute a small fraction of the overall cycle time. Historical data was collected and analyzed from the previous year to measure labor time at each step of the process and overall cycle time. These times vary drastically across models. Therefore each model had to be evaluated individually to determine applicability for JIT production.
Figure 13. Current State Map with MRP Scheduling

Note the amount of manual intervention in the scheduling process, represented in Figure 13 by the person connecting the MRP system to each process. This person is usually the shop floor supervisor but scheduling is also controlled through a customer manager. The customer manager is responsible for tracking all work orders and expediting any items that are behind schedule. MES has four customer managers that work somewhat independently resulting in a sub-optimization of resources. The shop floor supervisor is ultimately responsible for allocating resources. However the customer managers often interfere, especially in times of peak demand.

4.3 Model Selection

Similar to the EMID project, establishing supermarkets for all products was not practical considering the numerous low volume items produced as legacy models, spares, and for development purposes. An 80/20 analysis was completed to filter out the low volume products. The top 80% consisted of 22 different models with average monthly demand (output) ranging from 4 to 31 units. Figure 14 plots monthly demand relative to overall cycle time for these top 22 models. Overall cycle time is defined as the time to produce a unit from start to finish, including idle time. The cycle times are driven by various factors including product complexity, part availability, test capacity, and technician availability.
As shown in Figure 14, cycle time ranges from 2 to 23 days. The number of days shown does not include weekends, holidays, or overtime. Therefore 22 days represents an average month. This chart indicates that some products are more suitable for a supermarket than others. For instance, models A, B, and C are in high demand and require as little as 2 days to produce, thereby making them excellent candidates for JIT. On the other hand, models E, R, and V require almost a month to produce and therefore would not be suitable for JIT. It is important to note that these cycle times are real data generated under the current MRP based system and are dominated by idle time. Under the new system, it is assumed that these cycle times will decrease substantially, similar to the EMID process. However for planning purposes, the actual data was used to calculate supermarket size as will be discussed in the next section.

4.4 Future State

As noted previously, the future state of this project was clear from the beginning; establish a finished goods supermarket from which the customer may shop. The means to achieve such a goal however was not clear until the data was carefully evaluated. Given the extremely disparate processing times and the lack of coordination between functions, a traditional Kanban system with a feedback loop at each station was not feasible. A hybrid constant work-in-process or CONWIP system was selected as a more suitable process.
4.5 CONWIP Overview

CONWIP is a push-pull production system first described by Spearman, Woodruff, and Hopp in 1990. A CONWIP line maintains a constant WIP level by allowing new jobs to enter the production loop only as existing jobs are completed. The primary difference between CONWIP and traditional Kanban is that CONWIP pulls jobs from the front of the line and pushes them between stations elsewhere in the line, while Kanban pulls jobs between all stations. CONWIP is designed to deliver the same benefits of pull production for high-mix low volume operations that aren’t conducive to traditional JIT.

Figure 15. Future State Map with CONWIP System

4.6 Dual Supermarkets

The Future State Map, shown in Figure 15, illustrates the use of two separate feedback loops thus creating somewhat of a hybrid between traditional Kanban and CONWIP. Units are pulled through the critical steps; assembly and test, and pushed through the less variable steps; inspect, process, and final inspect. The rationale for using two loops rather than one complete loop is simply that the overall cycle time in most cases is greater than

---


the time between shipments. For example, consider model J that has an average cycle time of 1.5 weeks and an average demand of 2 units per week. In a one loop system, when a completed unit is shipped to the customer, a card is sent back to the front which will then trigger production of another unit. This unit will then take an average of 1.5 weeks to complete, but the customer needs the next unit within the week.

While it is possible to use one loop, it would require an undesirably large finished goods inventory. Establishing two loops cuts cycle time roughly in half and reduces the total amount of inventory to sustain the system. The major downside is that two loops require two supermarkets which complicate the system from a management perspective. The design and implementation of the supermarkets will be discussed further in the following sections.

The purpose of a supermarket is to serve as both a scheduling point for production and to act as on-hand inventory ready to ship at the customer’s request. In the CONWIP system described above, there is both a finished goods supermarket and work-in-process supermarket. Both behave in the same manner, the only difference being that the FG supermarket will be directly accessible by the customer and will therefore serve as the primary trigger for production.

A description of the system shown in Figure 15 is as follows. Each supermarket will have a predetermined size which serves as the target amount of inventory. As soon as the number of units falls below this target, a Kanban card is sent upstream to initiate the release of a new unit. When a spot is vacated in the FG supermarket, the card goes back to Test which releases a unit from the WIP supermarket, vacating a spot and sending another card back to Assembly. The number of Kanban cards is equal to the supermarket size according to the CONWIP strategy.

### 4.7 Supermarket Sizing

The supermarket sizing methodology was based on a Continuous Review, Reorder Point policy as illustrated in Figure 16.\(^{13}\) The CR/RP model assumes a fixed order quantity \(Q\), which is one because units are built individually, and replenishment time \(L\), which is the same as cycle time. The reorder point, \(R\), is defined as the inventory level that will trigger a reorder event. A reorder event is triggered when the total inventory (FG + WIP) falls below \(R\). In this case, \(R\) is synonymous with supermarket size and can be calculated as follows.\(^{14}\)

---


R = LTD + SS
LTD = Lead Time Demand
    = μ_d * μ_l
SS = Safety Stock
    = z√(v_d * μ_l + v_l * μ_d^2)

μ_d = average demand (units/month)

v_d = variation in demand

μ_l = average cycle time (in months, month = 22 days)

v_l = variation in cycle time

z = measure of service level (z = 1.65 for 95% SL)

---

Figure 16. Inventory Level under Continuous Review Reorder Policy\textsuperscript{15}

It is important to note that R represents the sum of the FG and WIP supermarkets. Individual supermarket sizes were determined based on the average ratio of Test Time to Assembly Time (TT/TA).

\[ R = R_{FG} + R_{WIP} \]

\[ R_{FG} = R/2 \times TT/TA \]

In most cases, this ratio was close to 1, which leads to equal supermarket sizes of R/2. If R is odd and TT/TA is 1, the 0.5 unit usually gets added to the FG supermarket because management preference is to have more units closer to completion.

The benefit to using this approach is that process variation is built into the safety stock. To be conservative, historical cycle time data including rework was used for the calculation. Similar to the EMID project, the expectation upon implementing the CONWIP system was to reduce cycle time which would then allow for a subsequent reduction in supermarket size.

A supermarket calculator, shown in Figure 17, was constructed as a tool for MES to use in conjunction with the Supermarket Control Chart, shown in Figure 18. This calculator has four inputs, highlighted in yellow, which are linked directly to MES's data query system. The supermarket sizes are automatically output and displayed in green. Other factors that may be adjusted include service level (z) and Test/Assembly ratio. Upon full implementation of the system, it would be necessary to recalculate supermarket sizes periodically to adjust for changes in demand or cycle time.

<table>
<thead>
<tr>
<th>Model</th>
<th>Units/Mth (ud)</th>
<th>Demand Var (vd)</th>
<th>CT Avg (ul)</th>
<th>CT Var (vl)</th>
<th>Lead time to Dem</th>
<th>Safety Stk</th>
<th>SM size</th>
<th>Test/Asy</th>
<th>FG size</th>
<th>WIP size</th>
<th>Cost/unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15.0</td>
<td>50.0</td>
<td>0.41</td>
<td>0.07</td>
<td>6.2</td>
<td>7.5</td>
<td>14</td>
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<td>6</td>
<td>$5,000</td>
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<td>10.0</td>
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<td>0.33</td>
<td>0.09</td>
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<td>7</td>
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<td>4</td>
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<td>35.0</td>
<td>0.50</td>
<td>0.12</td>
<td>6.0</td>
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<td>13</td>
<td>1.20</td>
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<td>5</td>
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<tr>
<td>D</td>
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<td>0.28</td>
<td>0.05</td>
<td>3.7</td>
<td>2.6</td>
<td>6</td>
<td>1.00</td>
<td>3</td>
<td>3</td>
<td>$25,000</td>
</tr>
</tbody>
</table>

Total SM Inventory $897,200

**Figure 17. Supermarket Calculator Sample**

Supermarket sizes were calculated with and without forecasted demand variation (vd) to evaluate the impact of level loading the production schedule. Eliminating vd reduced the total supermarket size by roughly 20%. As noted in the safety stock equation above, reducing cycle time variation (vl) would have an exponentially greater impact on R. However, cycle time variation is more of a systematic issue resulting from the various factors discussed in Chapter 1 such as low test yield and frequent part shortages.
4.8 CONWIP Pilot Program

As mentioned previously, the concept of a supermarket driven production schedule was primarily motivated by a customer request. The MES CONWIP team, including the author and manufacturing manager, met with customer representatives towards the end of the internship to discuss an implementation strategy. It was decided to begin with a pilot program that included the high volume items with relatively low process variation.

The customer calculated its own supermarket size based solely on its production forecast. The customer’s supermarket was compared to MES’s as a reality check. In most cases, the supermarket sizes were identical. The few differences were driven by long cycle times on certain products that were not factored into the customer’s calculation.

It was agreed that the supermarkets would have to be monitored continuously and would therefore be subject to periodic audits by the customer. In response to this request, a Supermarket Control Chart was developed for the MES management team as shown in Figure 18. Unfortunately, the pilot program was not scheduled to begin until after the end of the internship. However an experimental “pre-pilot” was executed in anticipation of the transition and is discussed briefly in the following section.

<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>WSM</th>
<th>Repair</th>
<th>FSM</th>
</tr>
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<tbody>
<tr>
<td>M</td>
<td>11/28</td>
<td>3</td>
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<td>3</td>
</tr>
<tr>
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<td>1</td>
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<td>2</td>
</tr>
<tr>
<td>Th</td>
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<td>0</td>
<td>3</td>
</tr>
<tr>
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<td>3</td>
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<td>3</td>
</tr>
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</tr>
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<td>1</td>
<td>2</td>
</tr>
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<td>2</td>
</tr>
<tr>
<td>Th</td>
<td>12/8</td>
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<td>1</td>
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<td>2</td>
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<td>3</td>
</tr>
<tr>
<td>F</td>
<td>12/16</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 18. Sample Supermarket Control Chart

4.9 Execution and Preliminary Results

In addition to the analysis discussed in the preceding sections, the pre-pilot required three major actions before getting started: select a Kanban system, construct a supermarket, and train the technicians to use the system.
Unlike the EMID project, it was not possible to use the product bins as Kanbans because the bins are sent out periodically to be washed. For this reason, laminated 3x5 cards were used to drive production. A Kanban board was used to display cards that represented vacant spots in the supermarket, therefore a card on the board served as authorization to build or test. An empty board indicated that all units were either at a supermarket or in process. As will be discussed further in the next chapter, management and utilization of these cards turned out to be more difficult than expected.

To construct the supermarkets, a space on the incoming Test rack and on the Final Inspect rack were designated and labeled accordingly. Placemats with photographs were attached to the shelves so that vacancies were easily identifiable. As the supermarket grows to include all MES models, space will likely become a constraint that has to be managed.

Because the pre-pilot included so few models, but involved so many people, it was difficult to select a concentrated group of technicians for training. The management team was reluctant to conduct an all-hands training session mainly because the process was in its infancy and would likely require several modifications before being finalized. Of the technicians that were trained, many were quick to point out that there was no prioritization process separating the experimental CONWIP system from the existing production process. The dual supermarkets and Kanban boards added to the confusion. Many of these issues would have to be addressed before officially rolling out the process for the customer.

4.10 Chapter Summary

Chapter 4 presents a strategic analysis that includes a description of the current scheduling process and the introduction of CONWIP. This chapter also discussed supermarket calculations, developed management tools, and identified issues from the pre-pilot trial, which will be discussed in greater detail in the next chapter.
Chapter 5: Lessons Learned

Though similar in concept, the two projects presented in this thesis posed very different challenges from a leadership perspective. This chapter discusses some of the roadblocks encountered during the internship and summarizes the lessons learned for driving change in a manufacturing organization.

5.1 Challenges with EMID Project

The EMID project, initially designed as a small assignment to help permeate lean into the organization, evolved into a major part of the internship. Relative to the second project, there were few difficulties in leading the workforce. The challenges were more related to technical issues such as understanding the MRP system and deciding on a bin sizing methodology. There was one instance where a technician was very reluctant to give up responsibility as required by the process change but this was handled with further explanation and compromise. Aside from this incident, the value stream mapping event, rearranging the shop floor, and training the EMID technician all went very smoothly.

There were a few external factors that contributed to the success of the project. First, there were only two technicians affected by the change, and both were involved early on in the process. Their contribution during the VSM event and willingness to learn a new system was critical to implementing a functional process. The other factor was a tremendous amount of support from MES management. The summer months are typically not as busy, so the team was able to meet once or twice a week which helped keep the momentum of the project rolling. In addition to relationship building, the learning that took place during the project was primarily on how to conduct a VSM event and best explain lean concepts to the workers.

The most discouraging aspect of the project was trying to change the ordering policies with the EMID suppliers to use a Kanban. The potential for savings on raw material inventory was enormous and seemed very attainable. However the MRP system was like a black box. Every person contacted to explain its capability had a different answer. By the time everything was straightened out, the internship was coming to a close and the inventory had not improved at all. Aside from the supply chain management issues, this project was considered a success and helped establish a positive attitude leading into the next project.

5.2 Challenges with CONWIP Trial

The CONWIP project was a completely different story. Unlike the EMID project, introducing Kanban cards and supermarkets across the organization involved at least 15-20 technicians. Many of the technicians and supervisors were unable to attend the VSM kickoff event due to a busy production schedule in the fall. With so many stakeholders and no available time, the author and management team were forced to design the CONWIP system with little input from the key stakeholders. When it came time to execute the pre-pilot program, there was a tremendous amount of confusion regarding the
Kanban cards and dual supermarkets. Had the entire team been involved from the beginning, or been able to take part in an extended training period, the pre-pilot might have had more success. Instead, the author attempted to train individuals informally without providing the opportunity for communication among different functions. The result was a somewhat disjointed process with Kanban cards getting mixed up or lost.

The strategic analysis and process design were beneficial as management tools for planning and development however the tactical elements were somewhat disappointing. The pre-pilot exposed problems that need to be resolved before the actual trial period and customer audits begin. Like any large scale process change, this will require close attention from either a manager or engineer that is able to dedicate a substantial portion of time to the project. With another major lean initiative on the horizon, namely transitioning from stationary work benches to a mobile assembly cart, MES management will have to be disciplined in allotting time for process improvement even it means building ahead of schedule to shut down production.

5.3 Leadership Take-aways

Although methods for successful change management are different for every situation, there were several lessons learned over the course of the internship that are transferable to any lean implementation project. The key take-aways are listed below.

- A leader needs to interact with team members both in a group and individually
- Key stakeholders need to be involved from the beginning
- Learning by doing is better than excessively planning

The first take-away might seem obvious, but in many large organizations, managers don't take the time to lead outside of a group setting. The one-on-one interaction fosters the relationship and establishes a sense of ownership for the employee. In addition, people have different styles and some team members may not feel comfortable contributing during a group meeting but are eager to do so offline. Perhaps not as common, but other managers are so busy interacting with their employees that group meetings are neglected. This is similar to what happened during the CONWIP project, which led to a disintegrated team and process. Group gatherings can create a team dynamic, reinforce the significance of the change, and allow for communication between team members. A lack of team engagements also tends to diminish the sense of urgency for a project.

The second lesson above is more specifically targeted towards lean implementation. As demonstrated during the CONWIP pre-pilot, not involving technicians early on created a situation of giving orders rather than asking for input. This style can be effective in some groups, depending on the workforce culture. Certain people would prefer to take orders over contributing, but most are going to respond more effectively when they've participated in the process redesign. The opposing argument can be made that fostering a democratic style in a manufacturing environment with dozens or hundreds of workers can complicate the issue unnecessarily. Either way, the employee culture should be considered before choosing a leadership style.
Another way of stating the last take-away above is to avoid “analysis paralysis” as they like to say in MES. During the EMID project, the team started to enter a phase of “analysis paralysis” by excessively planning rather than implementing. Fortunately, there were team members conscious of this concept who suggested that executing the plan was more important than scrutinizing over every last detail. This is especially important in a time constrained, high pressure environment like manufacturing. The sense of urgency is the driving force behind Kaizen bursts or action work-outs, where plants will shut-down production to make things happen immediately thus taking away the opportunity for negligence. Avoiding this trap is critical for driving change in an operations environment where shipping products is the first priority.

5.4 Conclusion

The design and implementation of a lean production system is a complex and multifaceted undertaking that requires both careful analysis of the process and timely execution through employee training and adaptation. This thesis discusses lean implementation in the context of designing pull systems for highly variable processes. The two projects carried out during the internship demonstrated unique challenges despite being similar in nature. From an operational perspective, the CONWIP system was difficult to implement because of the added complexity of multiple supermarkets and Kanban cards. The EMID project was easier to execute but revealed the need for ongoing management to realize the full potential of the newly designed system. In summary, pull production and lean implementation in general, should be approached with three entities in mind; the process, the stakeholders, and the organization. The process will drive the analysis while stakeholder acceptance and organizational culture will help determine the plan for execution.
Bibliography


