Operational Improvement and Mixed Model Value Stream Development for Gauge Production Line

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Abstract

Gauge production line in Company X has an average daily demand of 13 gauges now. And the demand expects to rocket to 26 gauges per day in 2011. However, the current daily throughput is 10 gauges.

The current state value stream map was constructed to understand current production and find out the waste. To eliminate operational waste, operator work load was balanced and corresponding standard work procedure for operators and production monitoring technique were developed. The daily production throughput increased by 30% from 10 gauges to 13 gauges.

To achieve the daily throughput of 26 gauges, the capacity of current line was analyzed and necessary improvements for flow were identified. Operator workload was re-balanced to meet the demand. Kanban system was suggested for production control. And to reduce the lead time, the production line was also recommended to schedule for mixed production.

Finally, the future state value stream map was constructed. The total lead time for electronics parts and mechanical parts from receiving to shipping was reduced from 100 days to 51 days and 57 days to 31 days respectively. And the processing time was reduced from 4.1 hours to 2.5 hours for each gauge.

Key words: gauge production, demand, daily throughput, value stream map, operator workload balance, standard work procedure, Kanban system, mixed production, lead time, processing time.

Thesis Supervisor: Kamal Youcef-Toumi
Title: Professor of Mechanical Engineering

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Chapter 1 Introduction

1.1 Company background

Company X is the world's leading oilfield services company supplying technology, information solutions and integrated project management for customers in the oil and gas industry to optimize reservoir performance. The company was founded in 1926, and today the company employs more than 79,000 people working in 80 countries. Company X supplies a wide range of products and services from formation evaluation, seismic acquisition and processing, well testing and directional drilling to well cementing and stimulation, artificial lift and well completions, and consulting, software, and information management.

Singapore Integration Center is one of the company's largest research, development and manufacturing factory. The Singapore Integration Center focuses on Artificial Lift products. The 550,000 square foot plant has a full suite of manufacturing operations, ranging from foundry works producing castings for pumps, a large machine-shop to machine some of the major component parts, to several assembly-shops and full Quality Control testing facilities. The center employs a make-to-order manufacturing model for most of its products. Most of the orders are sold to internal customers such as Company X's field services and other manufacturing centers [1, 2].

1.2 Introduction to main products

Three main production lines of the Singapore Integration Center produce the electric submersible pumps (ESPs), gas lift mandrels (GLMs) and downhole pressure/temperature monitoring gauges. And the downhole monitoring gauges production line is the focus of this project.

Artificial Lift (AL) is to use artificial means to facilitate the flow of oil from a production well. And Gas Lift (GL) and Electric Submersible Pumps (ESP) are two major types of Artificial lift (AL). Company X offers AL solutions for applications ranging from simple and economical environments to complex environments with high-temperature and high-pressure. Strength in AL products is a key component of Company X's strategy to grow in the production market. Figure 1-1 and Figure 1-2 are schematics of ESP and GL products by Company X Singapore, respectively. The figures show the structure and complexity of the products.

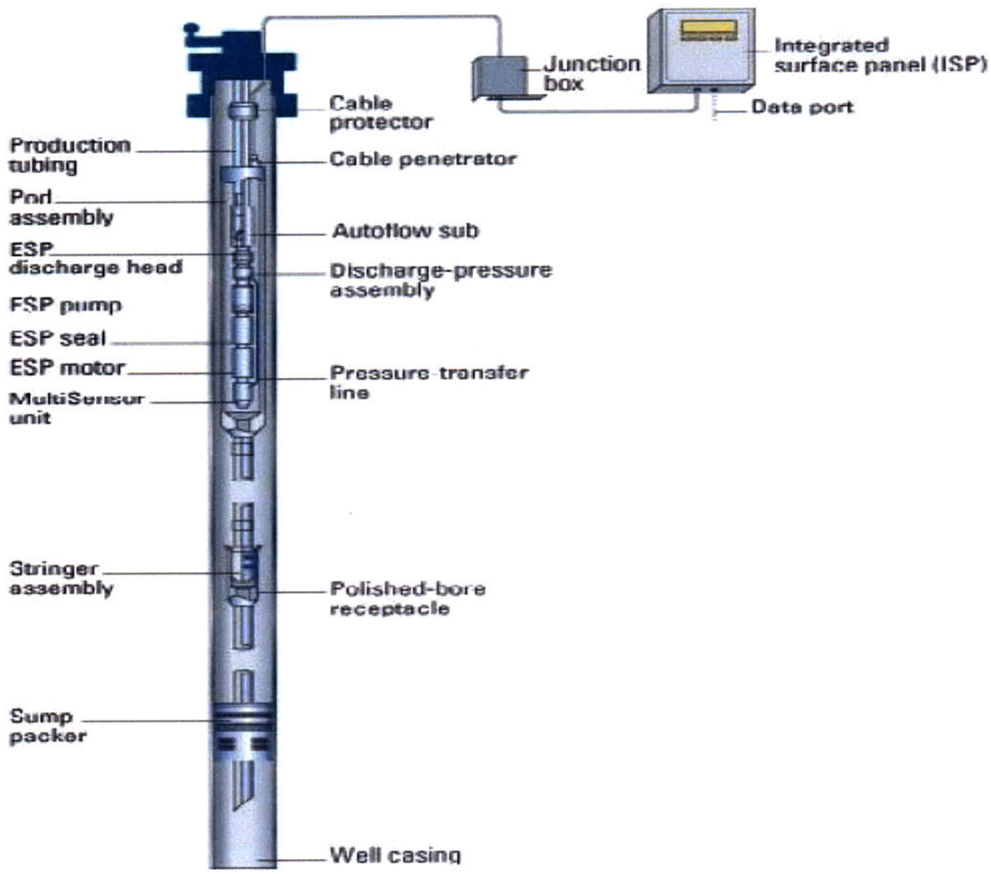

Figure 1-1 Schematic of ESP (top) product

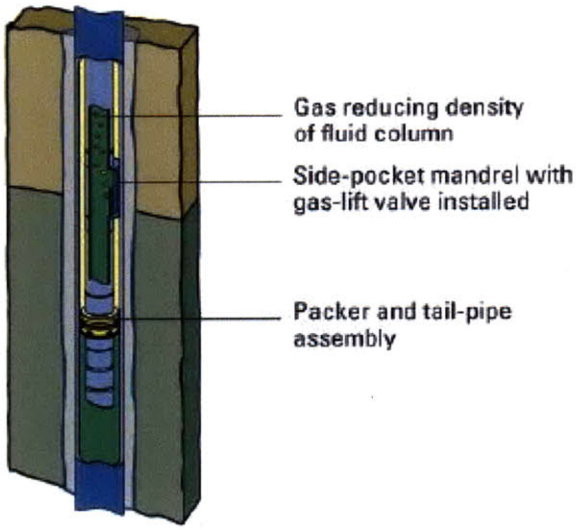

Figure 1-2 Schematic of GL product

ESPs are commonly used in deep wells where environmental conditions are complicated by high temperature (220°C) and high temperature. Therefore, Company X provides monitoring systems to complement the ESP product and ensure good performance and safe operation of the ESPs. The monitoring system includes the thermocouples, pressure sensors and vibration sensors, which together form the downhole gauge. It is built into the ESP products (Figure 1-3) and provides real-time feedback of the downhole operating environment. The information obtained by gauge helps engineers to predict potential catastrophic conditions and to prevent ESP failure. By integrating technology and service, Company X successfully provides an optimum lift system for the well and optimizes the pump and well performance while reducing costs for the customers.

Figure 1-3 Gauge (blue parts) integrated in ESP

1.3 Gauge production overview

1.3.1 Gauge products

The gauge products consist of three major parts: the gauge electronics which include the pressure and vibration sensors as well as thermocouples, the choke which holds the gauge electronics and the housing which insulates and protects the electronics from outside environment and provides the connections between the gauge and other parts of the ESP.

There are several types of gauges produced in Company X Singapore. Although their functions are similar, their demands, sizes, weights, and prices are different. According to the current situation, product A, B, C, and D are the most important four types of gauge products. And the demands for each type in year 2008 and 2009 are tabulated below. As shown in Table 1-1, due to the economic crisis in 2009, the total sales of gauge products drops from 3069 pieces in 2008 to 2246 pieces in 2009. The drop of the sales is mainly caused by the decrease of demand for A products, which consist of the majority of the demand in both 2008 and 2009. However, the sales of product B, C and D increased from 2008 to 2009.

Table 1-1 Demands of main products in year 2008 and 2009

Types	2008		2009	
	Sales	Percentage	Sales	Percentage
A	2,481	80.84%	1,291	57.48%
B	112	3.65%	336	14.96%
C	204	6.65%	253	11.26%
D	272	8.86%	366	16.30%
Total	3,069	100.00%	2,246	100.00%

1.3.2 Production process

The gauge production is performed in the monitoring lab. It is an 80-square meter enclosed clean room with controlled indoor environment. The temperature and relative humidity are controlled at 21°C and 50% respectively to protect electronic components. Figure 1-4 is a schematic of the layout of the gauge production cell. The layout will be introduced with the production process in following paragraphs as it facilitates the flow of the production.

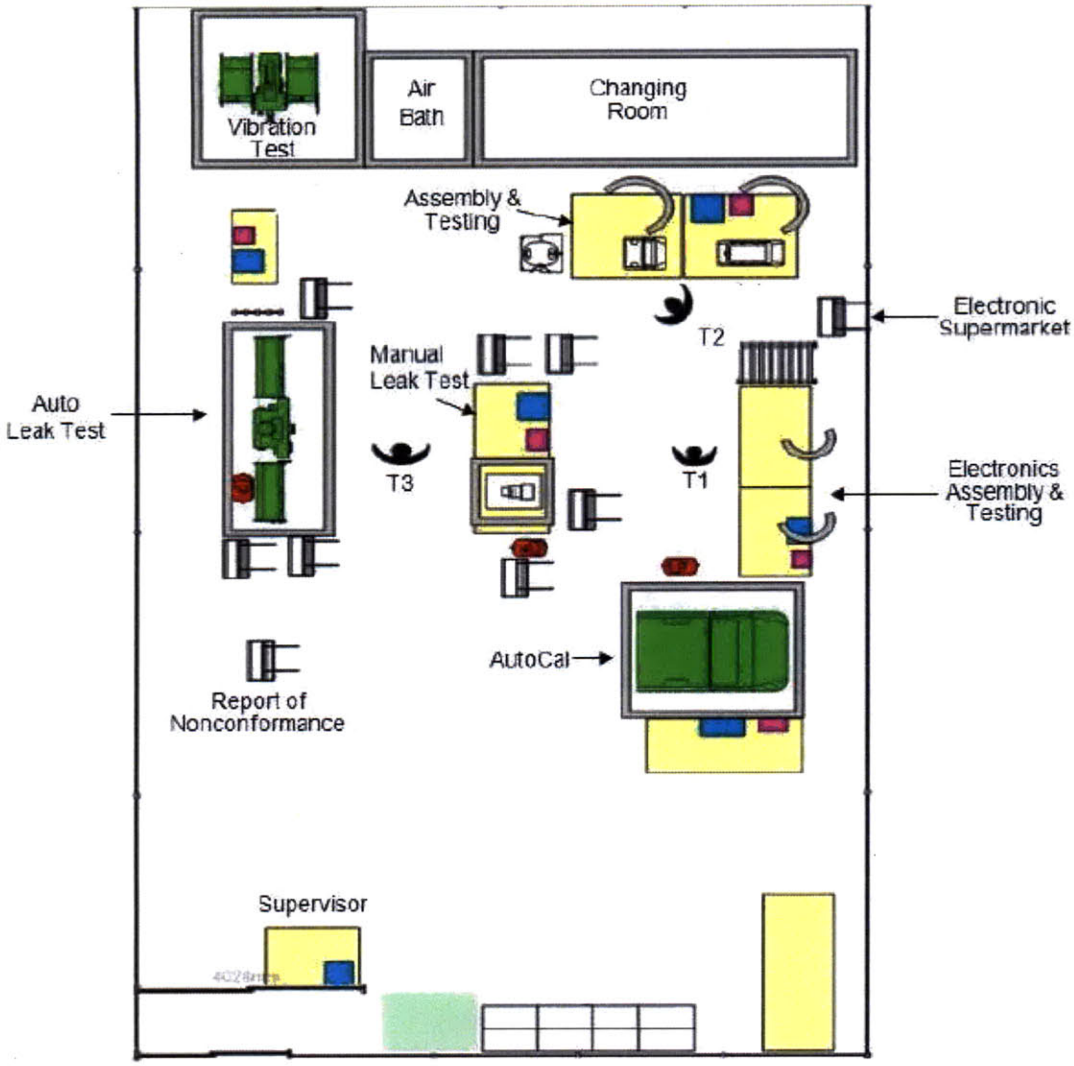

Figure 1-4 Schematic of the layout the gauge production cell

There are two major processes in assembling a gauge: the electronics assembly/auto-calibration and the mechanical assembly/testing. These two processes are decoupled by the electronic supermarket as shown in the production cell floor layout. They are initiated by different work orders, but the mechanical assembly activity needs the calibrated electronics as the essential part supply. Figure 1-5 shows the process flow of gauge production.

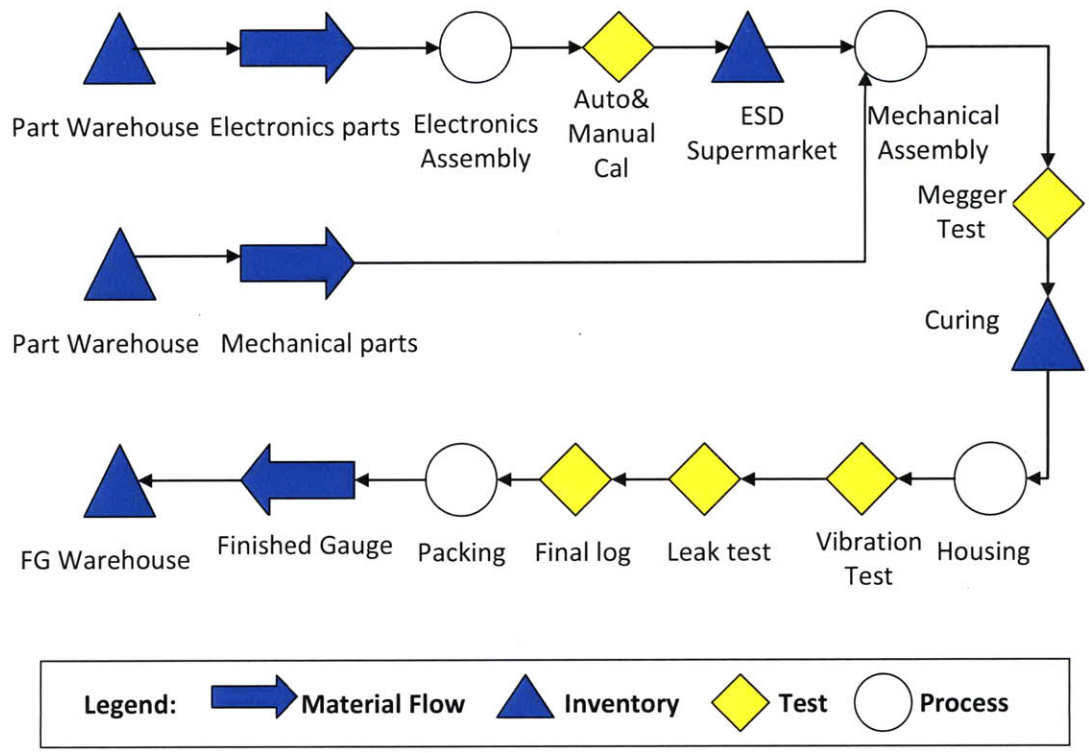

Figure 1-5 Process flow of gauge production

In the electronics assembly step, the gauge electronics is assembled from transducers and the printed circuit board (PCB) purchased from suppliers. The electronics then undergoes a 16-hour process in the auto-calibration machine in batches of 16, which performs tests with a range of temperatures and pressures to check the sensitivities of the sensors. If the PCB passes the tests on temperature and pressure, each one of them is then placed in a box and stored on the rack called "electronics supermarket". This supermarket is to buffer the mechanical assembly downstream.

In the mechanical assembly step, the calibrated electronics are first fixed into the choke, followed by the Megger test to check the functionality of the thermocouples. The choke-electronics subassembly is fixed into the steel housing after curing for 2 days. Then, the gauge undergoes the vibration test, where the gauge is placed on a shake table with various acceleration magnitude and frequency to check the sensitivity of the vibration sensors. The next step is the leak test, where high-pressure water is pumped into the gauge housing to check integrity of the gauge in the high-pressure downhole conditions. As shown in Figure 1-4, there is an auto leak test machine and a manual leak test station as an alternative resource. Finally the log test is performed in the manual leak test workstation to ensure every functional unit is intact. If the gauge passes all the tests, it is engraved with company logo, packaged with all test results in a disc and delivered to the customer. When a part of the gauge does not meet the specifications during a test, the failure is analyzed by the technician, who then decides whether the part will be reworked or reported and returned.

A report of non-conformance (RON) is generated for all parts which eventually fail the tests. These faulty parts are stored in the RON rack for a period of time and sent back to the suppliers if necessary.

1.3.3 Current production

The production operates with a make-to-order policy, or a pull system. After receiving orders from customers, the production planner schedules the production according to current production volume and capacity and assigns the due dates for the orders. Although many products share the production line, the daily work order includes only a single product type. Then work orders are released to the warehouse and the production line. Warehouse will help to prepare the raw materials according to the bill of materials (BOM), and deliver the crate of parts for a batch of products to the gauge production cell for assembly.

The lab is now running 2 shifts per day, 5 days per week. And there are usually two to three operators working in each shift. In the 1st shift, operator A works on the electronics assembly and auto-calibration; operator B works on the mechanical assembly and Megger test; and operator C works on the housing, vibration test, leak test, final log test and packaging. In the 2nd shift, two operators work on mechanical assembly and housing to packaging, respectively. Currently, the auto leak test machine is down. Thus manual leak test is conducted for all products. Although the work elements for each workstation are well learned by the operators, the work procedure for operators is flexible rather than standardized. Since operator C is taking charge of multi workstations, he tends to produce in batch for each workstation. Therefore, the Work-in-Process (WIP) inventory level is high.

Currently, the daily total output for this assembly line is about 10 gauges on average. However, the current demand is more than the daily output, which is about 14 gauges per day. To remain competitive in the market, the production line must improve the throughput immediately.

The thesis will indicate the problem in the production line and state the objective in Chapter 2. In Chapter 3, a solid theoretical background will be provided. Then the methodology with preliminary analysis will be illustrated in Chapter 4, and the results will be shown in Chapter 5 with discussion. Finally, recommendations according to the study will be provided for the company.

Chapter 2 Problem Statement

Figure 2-1 shows customer demands for products A-0, A-1, A-d, B, C, and D from year 2008 to year 2013.

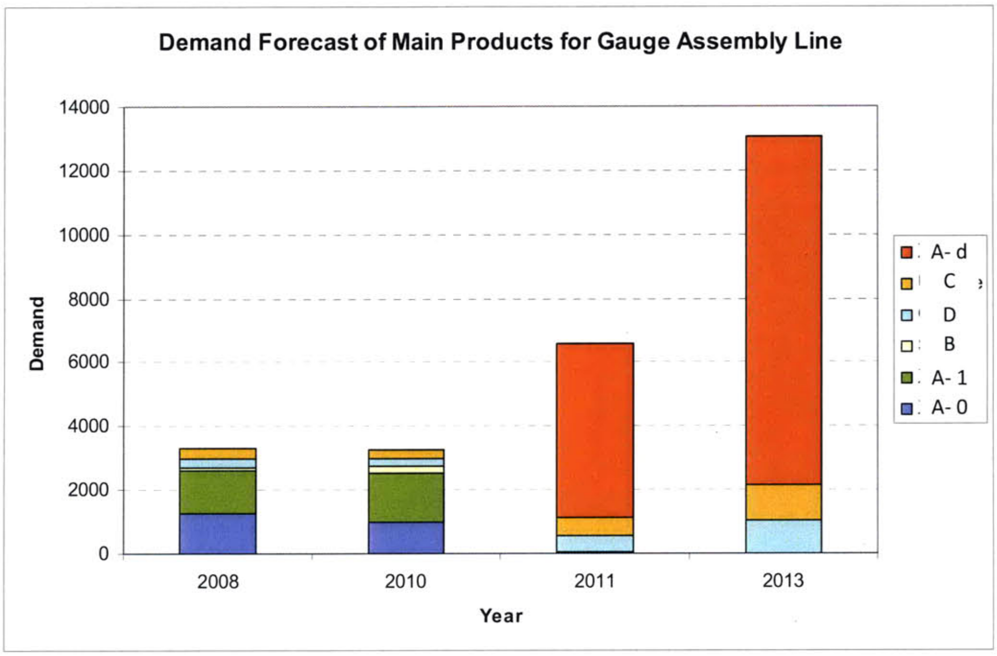

Figure 2-1 Demand forecast of main products for gauge assembly line

As illustrated in Figure 2-1, the customer demand forecast is increasing dramatically in next few years. The current demand is about 3200 pieces per year. The demand is expected to double to 6200 pieces in 2011. What is more, the forecast demand is rocketing to 13,000 pieces in 2013. In another words, the daily demand is about 14 pieces in 2010, 28 pieces in 2011 and 58 pieces in 2013. However, currently, the production line can only build 10 gauges per day on average, which is too slow to fulfil the rapidly increasing demand. Under these circumstances, the Gauge production line in Company X Singapore realizes it is urgent for them to improve the throughput in order to remain competitive in the market in both short run and long run. The team focus on different areas to achieve the improvement. This thesis describes the operational improvement for the current production line and development of the mixed model value stream for the future production line. Work by Ren [3] focuses on process improvement and work by Junying [4] focuses on floor layout improvement.

2.1 Project Motivation

As mentioned in previous section, with 2 shifts per day, 2 to 3 operators per shift, the current production rate is about 10 gauges per day. However, the daily demand is about 14 gauges per day (assume 20 working days per month). Therefore, backlogs are accumulating and operators are always working OT to catch up backlogs. The company is thus considering several options in order to have the production meet the demand: analysis the production line capacity; the possibility of acquiring additional machines; and the possibility of hiring more operators. As observed during daily production, operators tend to work batch by batch at each workstation, and some of the operators actually have plenty of idle time when machine is running. Thus there are opportunities to improve the production line by balancing the operator workload and redesigning the standard work procedure. And after rebalancing the workload, measures can be implemented in the production line to monitor and control the production.

As the forecast demand doubles in 2011, the company needs to know what changes need to be implemented to meet the demand. For instance, they want to identify the bottlenecks of the production line in advance, and plan for capacity expansion accordingly. Similar to current situation, the company also needs plan on operator workload balance to achieve the high production efficiency in future state. With these kinds of information available, they can train the operators in advance. Also measures should be established for production control and WIP control for the future state. To achieve higher customer service level, the production line would like to reduce the lead time to customer as well. To shorten the lead time, the production line is expected to be flexible and be able to produce a mix of products within one day. Therefore, it becomes important to establish scheduling tools to facilitate the mixed production.

2.2 Objectives

This project aims to improve the current operation of the production to meet the current demand as well as to develop a future state mixed model value stream for the Gauge production line. The detailed objective is outlined:

For current state:

i. Construct current state value stream map.

ii. Balance operator workload and design standard work procedure.

iii. Size for the WIP level between workstations.

iv. Identify the pitch, which is the monitoring time frame for production.

For future state (2011):

i. Identify bottlenecks and improvements needed.

ii. Balance operator workload and design standard work procedure.

iii. Establish Kanban system for production control.

iv. Size FIFO lanes and supermarkets.

v. Create scheduling tools for mixed production.

vi. Construct the future state value stream map

Chapter 3 Literature Review

Gauge production line is a mixed model production line. The concepts, definitions and tools regarding creating the mixed model value stream will be reviewed in this chapter to provide a theoretical background for the project.

3.1 Mixed model production

Mixed model production is to use the same value stream to produce a mix of products. The production line must deliver the right mix of products according to customer demand, which means the production line can produce the right quantity of a specific product when the customer wants it. [5]

In the mixed model production, a group of products that go through the similar processes and equipments and contain similar work content are treated as one product family. The total demand for the product family is reviewed as a whole for production planning. It makes the production line more flexible in responding to customer demand. [5]

3.2 Value stream mapping

Value Stream Mapping is a lean manufacturing tool to visualize the flow of value (materials and information) from the raw material to the customer. The implementation of value stream mapping follows the steps [5-7]:

i. Identify and select a product family;

ii. Create current state value stream map by taking a tour of the shop floor (identify the process steps, time, inventory level and so on).

iii. Assess the current flow and identify the waste.

iv. Create a future state value stream map.

v. Create implementation plan and implement the future state through continuous improvement.

3.3 Takt time and planned cycle time

Takt time measures the customer demand rate. Takt time synchronizes the pace of production with the pace of sales by telling the production line how fast they should produce. The time needed to complete work on each workstation need to be shorter than the takt time in order to fulfill the customer demand [5].

Takt time is calculated by dividing the total effective working time by the total demand for all products running through the process:

$$\text{Takt time} = \frac{\text{Effective working time}}{\text{Sum (Demand during that time)}}$$

Planned cycle time is usually targeted at 92% to 95% of the takt time, to allow for operator fatigue, minor interruptions in the cycle and the variations in the work content.

3.4 Time study

Time study is a method to establish operator productivity standards. Time study divides a complex task into small and simple steps, and the sequence of the steps to perform the work is carefully studied to detect and eliminate wasteful motion, and the precise time taken for each correct motion is measured. The concept was pioneered by the US industrial engineer Frederick Winslow Taylor (1856-1915) and developed by Frank Gilbreth (1868-1924) and Dr. Lillian Gilbreth (1878-1972) [8].

3.5 Machine capacity

Since the time a machine required to perform its work is usually fixed and not easily changed, it is critical to check the machine capacity to support production. On the other hand, labor time is more flexible. Thus it is easier to add or subtract number of operators in a production line.

The number of machines required at each process is calculated by dividing the total time needed to produce to demand by the total effective working time of the equipment during the time that demand is calculated. The total time needed is related to the cycle time of each product, the demand of each product, the failure rates of products going through the equipment and uptime in percentage for the equipment [5]. Therefore:

$$\text{Number of equipment needed} = \frac{\text{Total time needed}}{\text{Effective working time}} = \frac{\text{Sum (cycle time} \times \text{(demand} \div \text{(1-failure rate)))} \div \text{machine uptime in \%}}{\text{Effective working time}}$$

3.6 Operator balance chart

As a visual display of the number of operators and the cycle times at each operation of a particular process, the operator balance chart is created by showing the operations and number of operators on the x-axis, and the cycle time of operation and Takt time/planned cycle time on the y-axis. The operator workload balance is created to understand the work that to be performed at each station for each product and it is a useful tool to create continuous flow [5].

3.7 Standard work

Standard work is a precise description of each work activity, including the work sequence of specific tasks, cycle time and Takt time [9]. Standard work is created to facilitate the production. By following the standard work, any operator should be able to perform the amount of work required in the same amount of time, with good quality, without risk to health or safety [5]. Standard work aims to drive out variability. It requires engineers and operators continuously work together, eliminate waste and develop the standards.

Visual methods could be implemented to facilitate the standard work. Pictures, icons and symbols in the standard work visual sheets can provide operator a quick reference and remind them of the work contents and sequences.

3.8 Kanban

Kanban is a signaling device that gives instruction for production or conveyance of items in a pull system [5, 10]. It's also used to perform kaizen by reducing the number of Kanban in circulation, which could highlight the problems of the production line.

3.9 FIFO and supermarket

FIFO stands for "first-in, first-out". It means that material produced by one process is used up in the same order by the next process. When a FIFO queue becomes full, the upstream supply process must stop producing until the downstream has consumed the inventory. FIFO lane is used when a continuous flow is impractical [5].

Supermarket is a controlled inventory of items which is used to schedule production at the upstream process. Two basic models used for sizing the supermarket are continuous review and periodic review models [11].

In the continuous review model, it's assumed that the demands in non-overlapping time intervals are independent, the inventory is continuously reviewed, re-order with a fixed order quantity Q happens when the inventory level reaches the order point R, and the replenishment lead-time is a constant L. The order quantity Q could be determined according to the economics of quantity (EOQ) model. Assuming the demand is normally distributed, R is set as $\mathrm{R} = \mathrm{L}\mu + z\sigma\sqrt{\mathrm{L}}$, where μ is the average demand, σ is the demand variation and z is the safety factor calculated according to targeted customer service level. And the expected inventory level is the sum of the cycle stock and safety stock, which is:

$$\begin{aligned}\text{Expected inventory level} &= \text{cycle stock} + \text{safety stock} \\ &= \frac{\mathrm{Q}}{2} + z\sigma\sqrt{\mathrm{L}}\end{aligned}$$

In the periodic review model, it's assumed that the demands in non-overlapping time intervals are independent, the replenishment order is placed on a regular cycle with interval r, called review period, and at each replenishment epoch, the amount equal to the demand since the last replenishment epoch is ordered. The replenish lead-time L is a constant. Thus, the replenishments are received at times $t = r + L$, $2r + L, 3r + L$, and so on. Assuming the demand is normally distributed, the base stock level B, which is the starting inventory level and the minimum inventory to maintain effective and continuous operations, is calculated as $B = (r + L)\mu + z\sigma\sqrt{(L + r)}$, where μ is the average demand, σ is the demand variation and z is the safety factor calculated according to targeted customer service level. And the expected inventory level is the sum of the cycle stock and safety stock, which is:

$$\begin{aligned} \text{Expected inventory level} &= \text{cycle stock} + \text{safety stock} \\ &= \frac{r\mu}{2} + z\sigma\sqrt{r + L} \end{aligned}$$

3.10 Pitch

Pitch refers to the management time frame, which is used to measure the performance of production line according to the schedule. A process not producing to takt indicates a problem. And the production line could react to the problem immediately [5, 12].

The tools mentioned above will work together to realize the mixed production in the Gauge production line.

Chapter 4 Methodology

To improve the production line to produce to demand, the author starts by identifying the product family, collecting data for different products, and constructing the current state value stream. Then, the author will continue work not only in implementing immediate improvements for current state production but also in developing the mixed model value stream for future state production.

4.1 Identify product family

Since Gauge production line is a mixed model production line, product families must be identified. A product family matrix has been developed. The products require 80% of the same processing steps and with similar product characteristics have been grouped into one product family. Table 4-1 shows the product family matrix with the product families identified for Gauge production line. As shown in Table 4-1, product A, B and C follow exactly the same processing steps, from warehouse kitting to assembly and test, and final packing. Therefore, they were grouped together as product family A. On the other hand, product D, E and F have their own different processing steps. For example, product D skips the leak test and final log. Also, product D requires different process for gauge assembly, and it is performed in a different gauge assembly workstation. Similarly, product E and F have additional steps to complete compared with product family A. Thus, each of these three product types represents its own product family.

Product family A represents about 90% of the total demands. Therefore, this project will focus on product family A. All the resources covered in the discussion are assumed to be dedicated to product family A.

Table 4-1 Product family matrix

Workstation	Description	A-0	A-1	B	C	D	E	F
WHSE	Warehouse Kitting	X	X	X	X	X	X	X
Kitting	Cleaning and moving parts inside the lab	X	X	X	X	X	X	X
Electronics Assembly	PCB boards assembly	X	X	X	X			
Autocal	Auto Calibration	X	X	X	X	X		
Gauge Assy 1	Assembly + Test 1	X	X	X	X		X	X
Housing	Housing	X	X	X	X			
Vibration	Vibration Test	X	X	X	X	X		X
Auto Test / Manual test	AutoTest/Manual Leak Test and Final Log	X	X	X	X		X	X
Gauge Assy 2	Assembly + Test 2					X	X	
Sub-con	Proof Test (Wi-Fi)						X	
WIFI/CTS Assy	Power Up 1						X	
Sub-con	E-Beam Welding						X	X
WIFI/CTS Assy	Power Up 2							X
Sub-con	BJ Hydrostatic Test							X
WIFI/CTS Assy	Power Up 3							X
Packing	Packing	X	X	X	X	X		X
MATS	MAT (Quality Check)	X	X	X	X	X		X
Product Families		**A**				**B**	**C**	**D**

4.2 Data collection

The first step to study the production for product family A was to collect data on the demand of each product, the effective working time, the cycle time for each process, the yield rate of each process, the up time for each equipment, the raw material, WIP and finished goods inventory level. Date collection also involved communication with production line engineers, planners and operators. For instance, the yield rate and up time for each process were acquired from the engineers, and the information about demand and inventory was provided by planners.

In particular, time and motion study for every activity of each process for each product in product family A was carried out to determine process standard time. The time study worksheet used in this project is shown in Appendix. Videos were taken to identify the tasks for each work element, to provide reference for motion study, and to record the time needed for each work element. Same task is repeated by operators to allow the calculation of an average time. For tasks requiring a lot of manual work, 10% of the average time was added as allowance for variations.

The standard time for each process for products A-0, A-1, B and C has been summarized in Table 4-2 to 4-4. As noticed from the tables, product A-1 and product C have the same timing for each processing step. And product A-0 requires slightly longer time for packing than A-1. Additional time is required for product B electronics assembly and gauge assembly because the PCB is more complicated and it has additional remote feedthroughs to install than products A-0 and A-1. Moreover, since product B has vibration sensors in all three axes, it needs run vibration test for three directions while products A and C need run vibration for only one direction.

Table 4-2 Standard work time (product A-1/C)

Work Element	Batch size	Time Element (mins)	
		Manual	Auto
Electronics Assembly	16	160	
Auto Cal Setup	16	70	
Auto Cal Auto Run	16		720
Auto Cal Unload	16	40	
Manual Power Up	16	144	
ESD Packing	16	25	
Gauge Assembly	1	60	
Housing	1	7	
Vibration Setup	1	11	
Vibration Auto Run	1		12
Vibration Unload	1	2	
Manual Leak Setup	1	11	
Manual Leak Run	1		15
Manual Leak Unload	1	4	
Final Log	1	10	
Packaging	1	11	

Table 4-3 Standard work time (product A-0)

Work Element	Batch size	Time Element (mins)	
		Manual	Auto
Electronics Assembly	16	160	
Auto Cal Setup	16	70	
Auto Cal Auto Run	16		720
Auto Cal Unload	16	40	
Manual Power Up	16	144	
ESD Packing	16	25	
Gauge Assembly	1	60	
Housing	1	7	
Vibration Setup	1	11	
Vibration Auto Run	1		12
Vibration Unload	1	2	
Manual Leak Setup	1	11	
Manual Leak Run	1		15
Manual Leak Unload	1	4	
Final Log	1	10	
Packaging	1	13	

Table 4-4 Standard work time (product B)

Work Element	Batch size	Time Element (mins)	
		Manual	Auto
Electronics Assembly	16	192	
Auto Cal Setup	16	70	
Auto Cal Auto Run	16		720
Auto Cal Unload	16	40	
Manual Power Up	16	144	
ESD Packing	16	25	
Gauge Assembly	1	90	
Housing	1	7	
Vibration Setup 1	1	11	
Vibration Auto Run	1		7
Vibration Setup 2	1	3	
Vibration Auto Run	1		7
Vibration Setup 3	1	3	
Vibration Auto Run	1		7
Vibration unload	1	2	
Manual Leak Setup	1	11	
Manual Leak Run	1		15
Manual Leak Unload	1	4	
Final Log	1	10	
Packaging	1	11	

Other data collected will be reflected in the current state value stream map in Chapter 5.

4.3 Create the current state value stream map

The current Takt time was calculated. There are two shifts everyday. And each shift is 8 hrs, with two 15-mins tea break and one half-hour lunch/dinner break. The first shift is from 7:30am to 3:30pm. And the second shift is from 3:30pm to 11:30pm. So the effective working time is 7 hrs per shift and 14 hrs per day. The total demand in 2010 is projected as 3011 pieces for product family A as shown in Table 4-5.

Table 4-5 Demand forecast 2010 for product family A

	A				
Product	**A-0**	**A-1**	**B**	**C**	**Total**
Demand 2010	980	1528	225	278	3011
Percentage	32.55%	50.75%	7.47%	9.23%	100.00%

Assuming there are 12 months per year and 20 working days per month, the daily demand is 13 pieces.

Therefore, Takt time in 2010 = $\frac{14\text{hrs} \times 60\,\text{min s/hr}}{13\text{ pieces}}$ = 64 mins.

The production follows the steps as introduced in Chapter 1. There are two main flows for the product family: the electronics assembly/auto calibration flow and the mechanical assembly/testing flow. The existing process has been mapped out by walking through the each of the two flows, with the processes being shown as process boxes on the map. The data boxes were added in the map according to the collected data to record the cycle time, uptime, failure rate and number of operators. Any place with inventory accumulated in the flow was indicated. The information flow was created by interviewing the planners, supervisors and operators to find out how the operators knew what to build next. Finally, a lead-time ladder, which compared the total lead time (L/T) to total processing time (P/T), was added in the map. The mapped value stream will be shown and discussed in next chapter, section 5.1.

4.4 Analyze the current production line for improvement

According to the preliminary analysis, the current production rate cannot satisfy the current demand. Since the machine cycles may be fixed and not easily changed, a check to ensure the production line has enough machine capacity to support the proposed Takt time must be performed. The equipment capacity was analyzed for auto calibration machine, vibration test machine, manual leak test and final log workstation and packing workstation. As mentioned in section 3.5, the equipment requirement is calculated as:

$$\text{Number of equipment needed}$$
$$= \frac{\text{Total time needed}}{\text{Effective working time}}$$
$$= \frac{\text{Sum (cycle time} \times \text{(demand} \div \text{(1-failure rate)))} \div \text{machine uptime in \%}}{\text{Effective working time}}$$

For example, the sum (cycle time * demand) for vibration machine is calculated in table 4-6.

Table 4-6 Sum (Cycle time * demand) calculation for vibration machine

Product	Cycle time (C/T)	Demand	C/T x demand
A-0	25	980	24500
A-1	25	1528	38200
B	59	225	13275
C	25	278	6950
Sum (C/T x Demand) or Time Needed = 82925 minutes			

The total effective working time for two shifts per day is 14 hours, equivalent to 201600 minutes per year. With the failure rate of 1% and the uptime of 95%, the equipment required is thus equals to $\frac{82925 \div (1-1\%) \div 95\%}{201600} = 0.44$. Other equipments needed were calculated similarly and the results are shown in next chapter, section 5.2.1.

Labor is more flexible than machines. Operators could be added or subtracted to meet the Takt time. Thus, operator workload was studied and balanced to achieve higher production rate and meet the demand. Starting from products A, the work content data at each workstation was gathered. And options for operator balance to achieve the Takt time have been provided to allow trial runs. To buffer the variations such as operator fatigue and minor interruptions, the planned cycle time, which is 92% of the Takt time, was also plotted in the balance chart as a reference. Standard work procedure was designed accordingly. The pros and cons for each option were also discussed. After observing from the trial runs, suggestions for implementation were provided to the production line supervisor. Furthermore, the WIP levels between workstations were carefully sized to control the production. Last but not least, pitch was planned to be implemented to monitor the performance of the production line. The differences in operator workload balance for other products in the product family from product A's were also discussed.

4.5 Create the mixed model value stream for future state

The future state is targeted to fulfill the demand in 2011. As the total efficient working time is the same as in 2010, the demand in 2011 is expected to reach 6072 pieces for product family A as shown in Table 4-7, which is about twice as the demand in 2010. Therefore, the Takt time for the future state is expected to be half of the Takt time in 2010. The daily demand in 2011 for product family A is 26 pieces per day. And the Takt time is 32 minutes.

Table 4-7 Demand forecast 2011 for product family A

Product	A-d	B	C	Total
Demand 2010	5466	50	556	6072
Percentage	90.02%	0.82%	9.16%	100.00%

The capacity for future state production was evaluated first. Then the future state process flow and targeted cycle time after process improvement were identified. After that, operator workload was balanced to meet Takt time. Furthermore, the production strategy to be implemented was determined and discussed, e.g. the finished goods strategy and the establishment of the Kanban system, and the sizes of FIFO lanes and supermarkets were calculated accordingly. Moreover, the management time frame-pitch was specified. Very importantly, the scheduling techniques for mixed model production were discussed. The future state value stream was mapped out accordingly. The mapped value stream will be shown in Chapter 5.

Chapter 5 Results and Discussion

5.1 Current State Value Stream Map

Current state value stream of product family A has been mapped out and shown in Figure 5-1.

As shown at the top of the map, the company uses the material requirements planning (MRP) system for production planning and inventory control to manage the manufacturing processes. The planners forecast for the demands as well as the raw material requirements for 12 weeks. The forecast is updated monthly. After receiving the order request from the company's standard fulfillment system - web procurement system (WPS), the planners schedule for daily production according to the current production capacity and capability. The promised lead time to customer is about 3 months on average. Since the production line has two main flows decoupled by the electrostatic dissipative (ESD) supermarket, there are two separate job orders for each of these two flows. And the daily production order is for single product instead of mixed products. The job order for the electronics assembly flow is usually to prepare one batch (16 pieces) of PCBs per day. And the job order for the mechanical assembly/testing flow is to produce 10 gauges per day. Finally, the shipment schedule is released to the finished goods inventory.

As noticed in the map, there are different suppliers for the electronics parts and mechanical parts. The main electronics part is the printed circuit board (PCB). And the main mechanical parts are choke, choke bracket, top sub and bottom sub. The four main parts are treated as one pack of mechanical parts in the analysis. When the company expects a rise in the price of the electronics parts, they usually buy a large quantity of them such as 1-year's demand. It is easier for the company to hold electronics parts as the electronic parts occupy less space for storage. The lead time for electronic parts is as long as 9 months. As revealed in the value stream map, the company is currently holding 75-days inventory. On the other hand, the purchaser buys the mechanical parts more frequently –twice a month, to hold less raw material inventory. The lead time for mechanical parts is about 1 month. So the base stock level for the mechanical parts is about 1.5-months demand. And the expected inventory level is about ¼-month inventory plus safety stock. As shown in the value stream map, the company is currently holding 47-days inventory, which is about the base stock inventory level.

After receiving the batch production order for electronics assembly/auto calibration, the operator collects parts from warehouse and conduct 100% inspection for the PCBs. This operator is separated and not controlled in the production line. Then operator A in the production line takes charge of electronics assembly, auto calibration, manual calibration and packing processes. Each of these processes is conducted in batch of 16 because the auto calibration machine has to run the test in batch of 16. The failure rate for the production up to ESD supermarket is as high as 18.8%. It means that there are on average 3 PCBs failed for each batch produced. The ESD supermarkets hold 11-days' inventory. The high inventory level in ESD supermarkets is caused by the imbalance of production rate of the electronics assembly flow and gauge assembly flow. The electronics assembly flow can produce on average 13 pieces of gauges per day. However, the gauge assembly flow can only produce 10 gauges per day. Therefore, ESD supermarket level is getting higher and higher. In summary, the total processing time is 22.3 hrs for one batch of electronic parts up to ESD supermarket. However the total lead time is 90 days, of which 86 days are caused by the raw material inventory and ESD supermarket inventory. And the remaining 4 days is still about four times of the processing time. Improvement is expected to reduce the WIP. Further investigation suggests that standard work procedure could actually be designed and implemented to control the production and WIP. Since there are two auto-calibration machines available, the operator sometimes run two machines together. The practice increases the unnecessary WIP. The detailed work for standard work procedure design will be addressed in section 4.2.

When a production order is received for the mechanical assembly/testing flow, PCBs are pulled from the ESD supermarket and mechanical parts are issued from the warehouse. Operator B assembles the gauge and runs the Megger test. Then the gauge sits for curing for 48 hours. Operator C installs the housing onto the gauge and runs the vibration test, leak test and final log. Finally, operator C packs the gauge and sends the gauge to the finished goods crate. The total processing time for gauge assembly and Megger test ranges from 60 minutes to 105 minutes, while the lower cycle time is for product A and product C, and the higher cycle time is for product B. The total processing time for a gauge from housing to packing is about 79 minutes for product A and product C, and 116 minutes for product B, because product B needs to run vibration test in three axes. Finally, there are 7-days' finished goods waiting for shipping, as the shipping schedule is not standardized and usually the finished goods is shipped once a week or two weeks.

In summary, the total processing time for a gauge from raw material to finished good is about 4.1 hours plus 2 days for curing. However, the total lead time for the electronic parts is about 100 days and the total lead time for mechanical parts is about 57 days. In addition to the high raw material and finished goods inventory level, the reason for the long lead time is the unnecessary WIP due to batch production and un-standardized work procedure of operators.

Moreover, the 10-pieces daily production order for mechanical assembly/testing could not meet the current demand of 13 pieces per day. Both operator B and C work two shifts everyday. Operator C usually works for overtime (OT). By looking at the timing, the unbalanced workload for operator B and C is noticed. For instance, operator C becomes the bottleneck for the high runner product A and limits the daily production rate for the mechanical assembly/testing flow. Although the cycle time for operator C is long, it is usual to see him idle while a testing machine is running. Therefore, the operator workload balance to meet Takt will be discussed and created in next section. The corresponding standard work procedure and monitoring techniques will be developed.

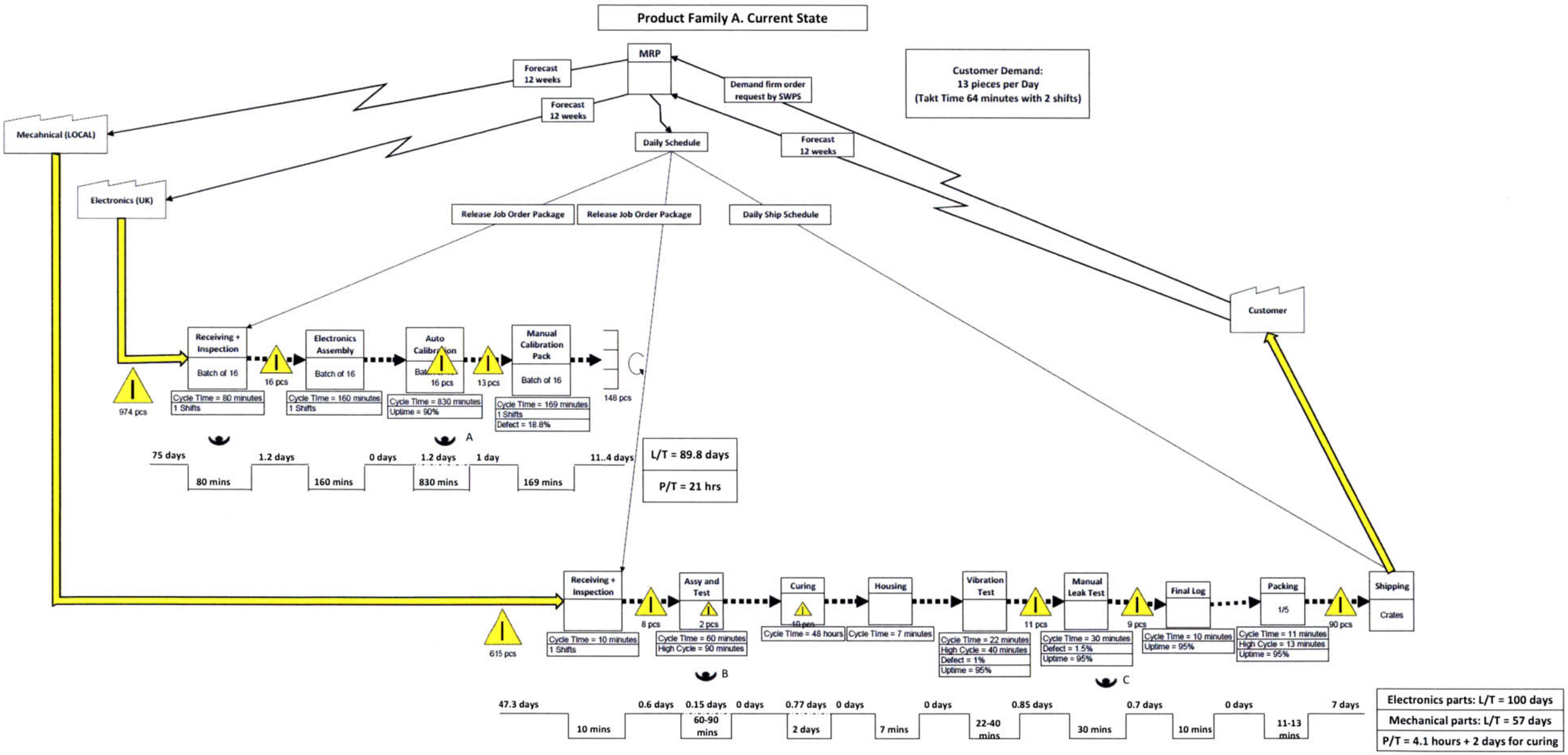

Figure 5-1 Current State Value Stream Map on 24th May 2010

5.2 Current production line improvement

5.2.1 Equipment support analysis

Before moving on to balance operator workload to meet Takt, the current capacity of the equipments has been analyzed to ensure they can support the Takt time. The equipments in the production line are auto calibration machine, vibration test machine, manual leak test and final log workstation and packing workstation for their corresponding processes. The calculated equipment requirement according to demand, cycle time, up time, failure rate and effective work time is shown in table 5-1 below.

Table 5-1 Equipment needed for product family A production in 2010

Equipment	Sum (C/T x Demand) (mins)	Up time	Failure rate	Effective working time (mins)	Equipment needed
Auto calibration	156195.6	90%	18.75%	345600	0.62
Vibration test	82925	95%	1%	201600	0.44
Manual Leak + Final log	120440	95%	1.50%	201600	0.64
Packing	35081	95%	0%	201600	0.18

Note that the effective working time for auto calibration is 345600 minutes, which is equivalent to 24 hours per day, while the effective working time for other machines is 14 hours per day with two shifts per day. The reason is that the auto calibration machine could run the test for a batch of 16 PCBs for 12 hours at night without operators present.

The numbers of equipments required shown in the last column. Only one machine for each process is needed for product family A. Currently, there are 2 auto calibration machines, 1 vibration table, 1 manual leak test and final log workstation and 1 packing workstation with an engraving machine in the production line. Although all these equipments are shared with other product families as well, one machine for each process is still considered sufficient considering the demand (about 10% of product family A) and cycle time (similar to product family A) for other product families. In particular, since there are two auto calibration machines available, it is recommended that one auto calibration machine could be dedicated to product family A to avoid disruptions for the production. The analysis in the project is based on the assumption that all the resources are dedicated to product family A.

By further investigating Table 5-1, it is found that the up time for auto calibration machine is lower than other machines', while the failure rate of products which are processed from the auto calibration machine is much higher than other machines'. Although one auto calibration machine dedicated to product family A can satisfy the current demand, as the demand doubles, triples or even quadruples in the near future as forecasted, the auto calibration machine may become the bottleneck. To solve the problem, the more efficient and cheaper way than acquiring additional machine is to improve the up time and product failure rate during the process. Engineers are working on improving the two aspects of the auto calibration machine and expect to achieve an up time of 95% and failure rate of 6.25% by the end of 2010. Equipment support analysis will be discussed again in section 5.3 for year 2011.

5.2.2 Operator workload balance

Three options for operator workload balance for product A have been provided. In this section, each option is discussed in detail with the operator standard work procedure. The WIP between workstations and pitch for each option are decided. And the strengths and limitations of each option are discussed. Finally, suggestions for implementation are illustrated according to the trial run result.

Option 1

Option 1 for operator workload balance to achieve Takt for product A is depicted in Figure 5-2. According to operator workload balance option 1 for product A, there are totally 3 operators needed in this production line. Similar to current operation, operator A takes charge of the electronics assembly and calibration flow, which includes the work elements of electronics assembly, auto calibration setup, unloading, manual power up and ESD packing. The flow is conducted in batch of 16 and the average failure rate for the flow is 18.75%, which means there are on average 13 PCBs produced for each batch of production. Therefore, the timing in Figure 5-2 for operator A takes 1/13 of the timing for one batch of PCBs. So, the total cycle time per gauge for operator A is equivalent to 33 minutes, which is 1 minute over the Takt time and 4 minutes over the PCT with 1 shift per day. Theoretically, one shift with one-hour's OT can produce one batch of PCBs and meet the current demand.

Operator B works at the mechanical assembly workstation. The work elements include choke assembly, board assembly and Megger test. The total cycle time for the operator is 60 minutes, which is 3 minutes below the Takt time and 1 minute over the PCT with 2 shifts per day. Thus, the operator B is expected to produce to demand with 2 shifts everyday.

Operator C works for housing, vibration test, leak test, final log and packing. The total cycle time is 56 minutes, which is 8 minutes below the Takt time and 3 minutes below the PCT with 2 shifts per day. Therefore, the operator is expected to produce to demand with 2 shifts everyday. The additional 2 minutes per cycle is used for walking time, since the operator takes charge of many workstations and needs walk between the workstations.

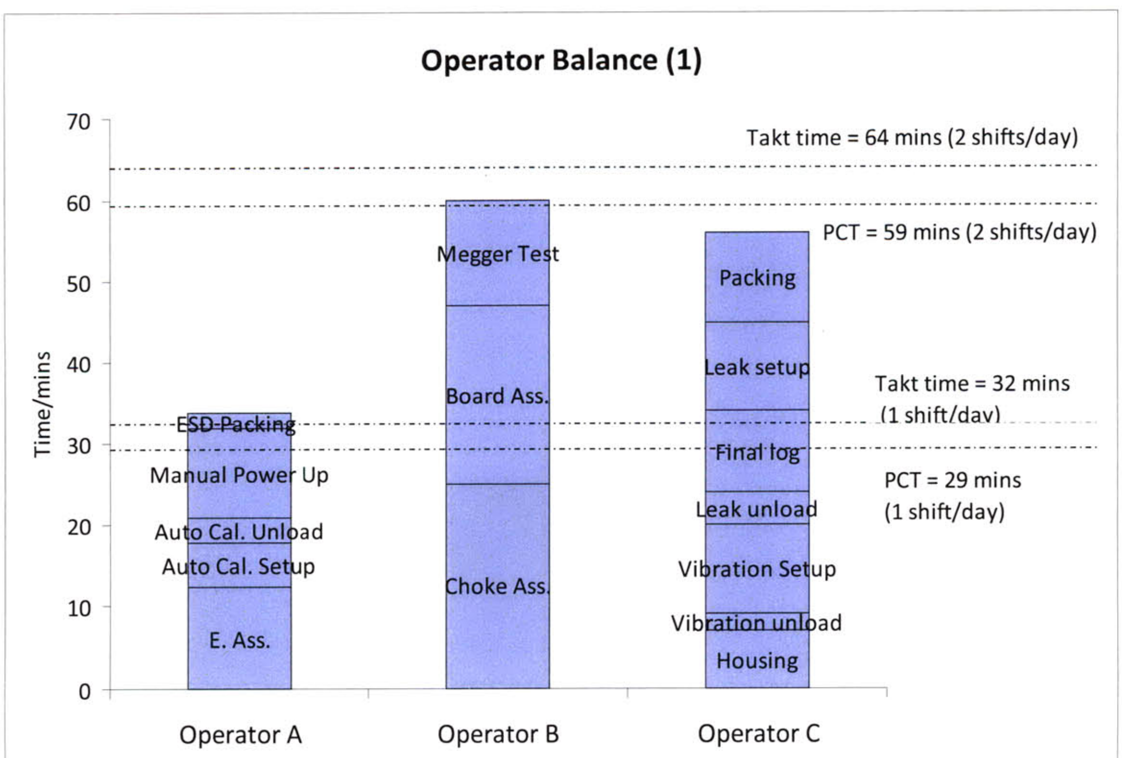

Figure 5-2 Operator workload balance for product A – option 1

To allow minimum WIP, the standard work procedure for each operator needs to be designed and discussed. Figure 5-3 shows the standard work procedure for operator A producing 1 batch of PCBs in the first shift of the day. Time scale for the first shift is shown in the y-axis. The operator sets up the auto calibration machine in the afternoon before leaving the company, then the machine auto runs for the whole night. And in the next morning, the operator firstly unloads the boards, then conducts manual power-up, packs and stores this batch and does electronics assembly for the next batch. The operator follows the standard work procedures for each process.

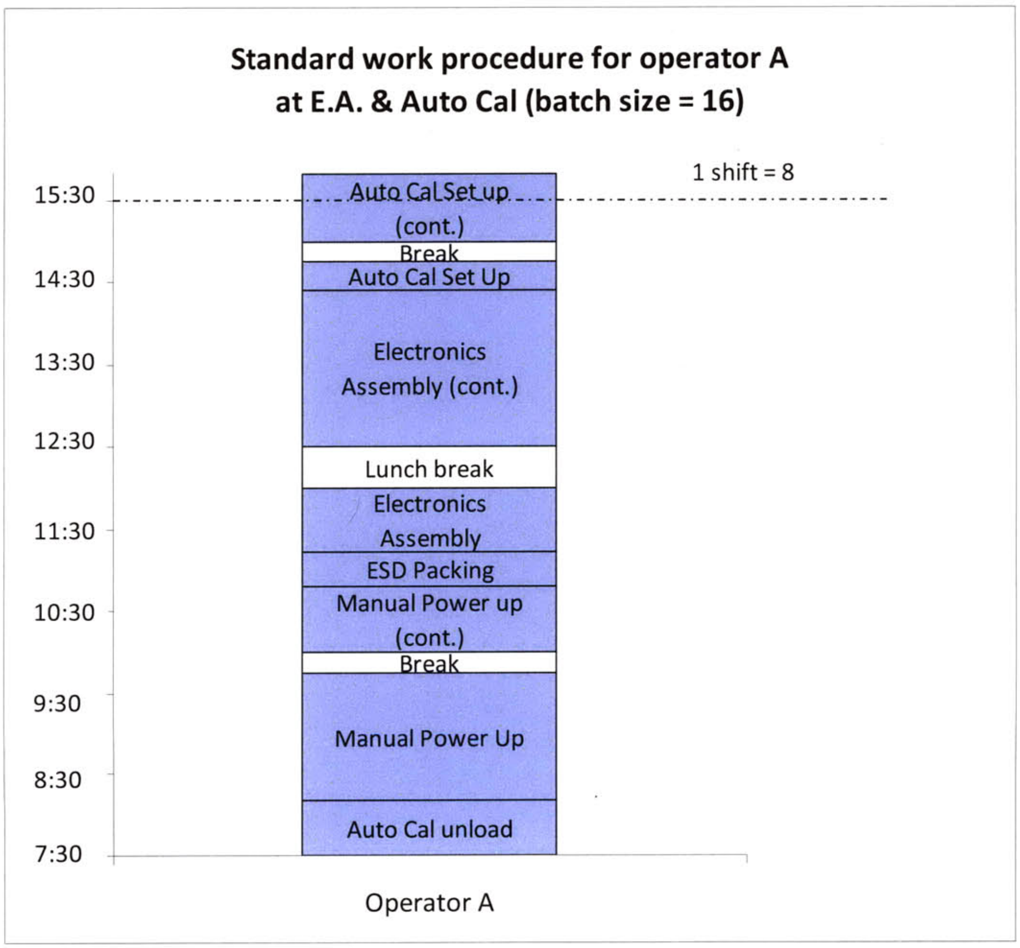

Figure 5-3 Standard work procedure for operator A

Operator B follows the standard work procedure for mechanical assembly process. The operator is expected to follow single piece production for mechanical assembly.

Figure 5-4 shows the standard work procedure designed for operator C. The first bar is the working procedure for the operator, and the second bar and third bar show the workstation status during each cycle for leak test workstation and vibration test machine respectively. Figure 5-5 shows the flow chart according to the standard work procedure for operator C. The design is basically to treat the flow as a small cell. The operator walks from workstation to workstation, works at the station, loads or unloads the gauge. The operator starts each cycle by installing housing for a gauge at the housing stand. Then he moves to vibration table to unload a previous loaded gauge and load for a new gauge. Next, the operator walks to the manual leak test and final log workstation, unloads the gauge from leak test, conducts final log for the gauge and load a new gauge for leak test. Finally, he goes to the packing area and packs the gauge for shipping. The operator follows the standard work procedures for each process.

The WIP between workstations include the ESD supermarket, curing station, FIFO lane between housing stand and vibration workstation, FIFO lane between vibration workstation and manual leak test/final log workstation, and FIFO lane between manual leak/final log workstation and packing station. Theoretically, the order to electronics assembly/calibration flow is 1-day's offset of the order to the mechanical assembly/testing flow. Thus 1-day's inventory in ESD supermarket would be enough for the downstream production. Since each gauge needs sit for curing for 2 days, the curing station itself is a FIFO lane with a maximum size of 2-days inventory. And the maximum sizes for other FIFO lanes are 1. To accommodate any failure at each workstation, buffer stocks could be added.

Pitch for operator A is 1 shift to produce 1 batch ESD packed PCBs. However, supervisor could monitor during 1 shift according to the timing/scheduling depicted in Figure 5-3. Pitch for both operator B and C is 1 hour, which means the supervisor should expect 1 gauge coming out from mechanical assembly station and 1 gauge moving to the shipping crate every hour. Score boards could be placed at the mechanical assembly station and shipping crate to facilitate the monitoring process. Any abnormality requires immediate investigation. And the operator, supervisor or engineer is expected to react to the problem on time.

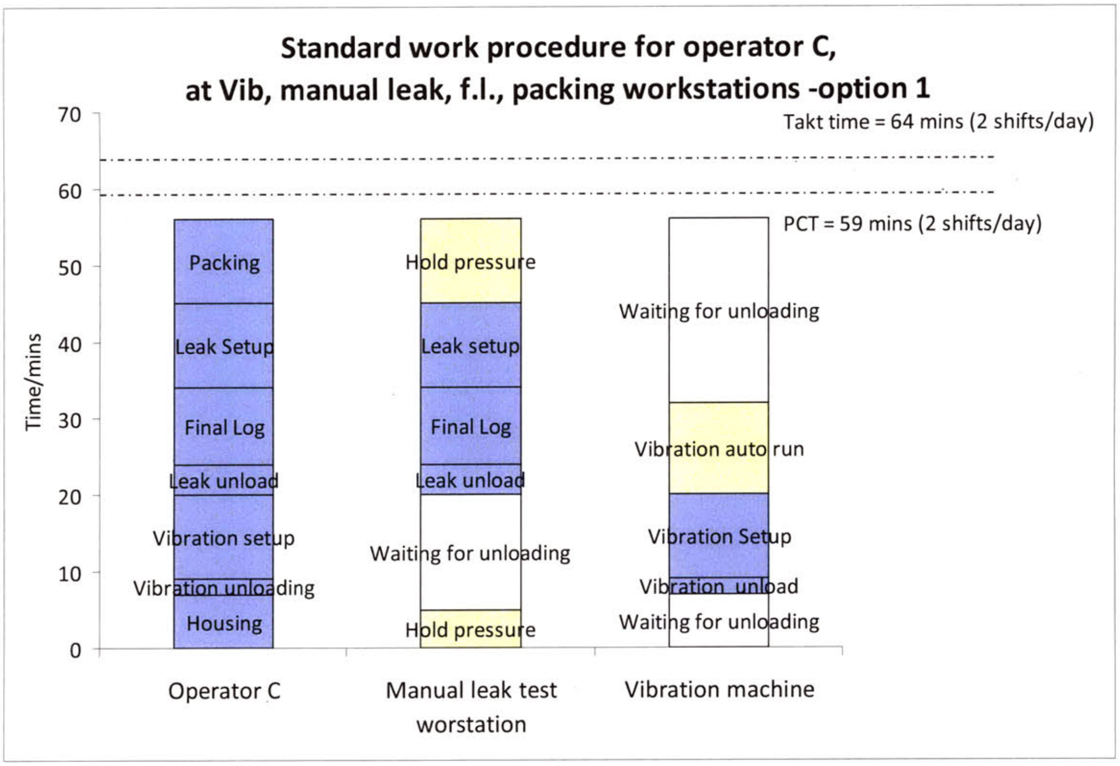

Figure 5-4 Standard work procedure for operator C for option 1

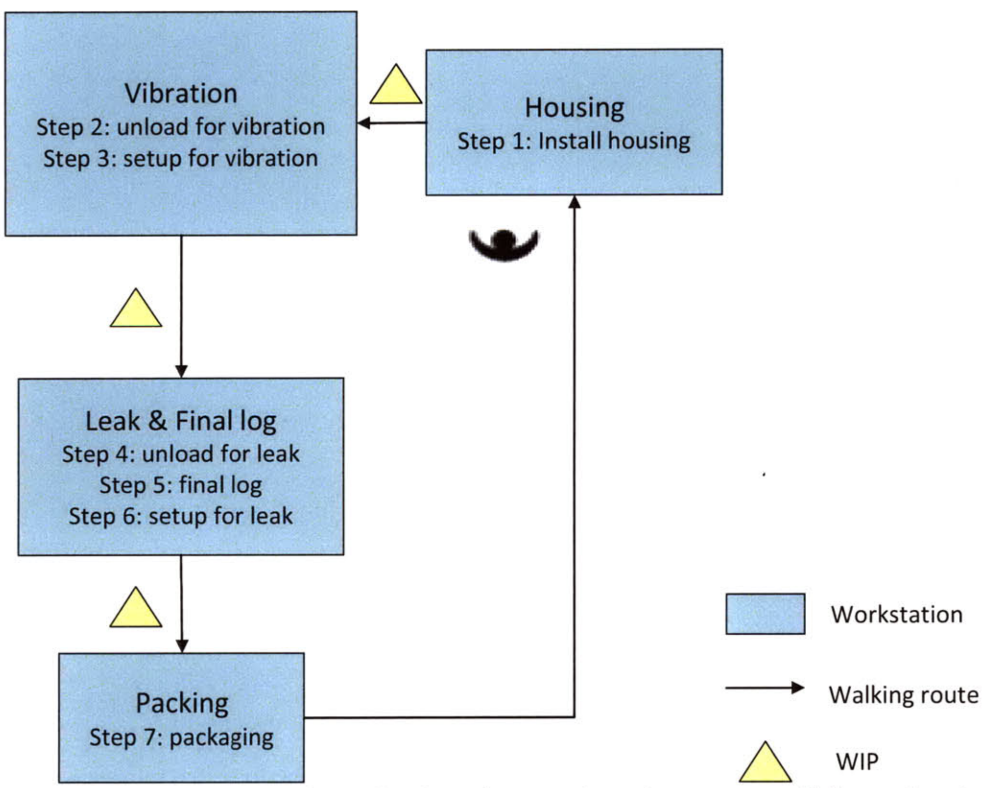

Figure 5-5 Flow chart of standard work procedure for operator C for option 1

The strengths of option 1 are: the work procedure design for operators, especially for operator C, has eliminated the operator idle time; the pitches for operator B and C are consistent and easy for management; the design facilitates the single piece flow of work for each operator; the design allows minimal walking for operator C covering 4 workstations; the work procedure is easy to remember; and buffer time is available for operator C. The limitations are: firstly, to implement this option, there are ergonomics issues to be considered, because the gauge is heavy and the walking distance between workstations is considerable; secondly, machine needs to be reliable enough to ensure the smooth flow of the processes; last but not least, as shown in Figure 5-4, for the manual leak test, after holding pressure for 15 minutes as required, the gauge sits at the leak test station for additional 16 minutes, and the operator is only able to check the test result and release pressure after he finishes vibration setup for another gauge. The delay is a waste of energy and also delays the reaction to problems. And similar situation occurs to vibration test. Thus, option 2 is designed to counter this particular problem.

Option 2

Option 2 for operator workload balance to achieve Takt for product A is depicted in Figure 5-6. Similar to option 1, there are 3 operators in the production line. And the standard work procedures for operator A and B are exactly the same as described in option 1. However, the standard work procedure for operator C is different and shown in Figure 5-7. And the flow chart according to the standard work procedure is depicted in Figure 5-8. The total cycle time for operator C now is 58 minutes, still below the takt time as well as the PCT. The operator installs the housing for gauge first. Then he moves to the vibration table and sets up one gauge for vibration test. While vibration test is running, the operator goes to the leak test workstation and setup for leak test. And he comes back to vibration table to unload the gauge, picks one gauge between leak test/final log workstation and packing station, packs the gauge and sends to finished goods crate. He moves to leak test/final log workstation again to unload the gauge and conduct final log for this gauge.

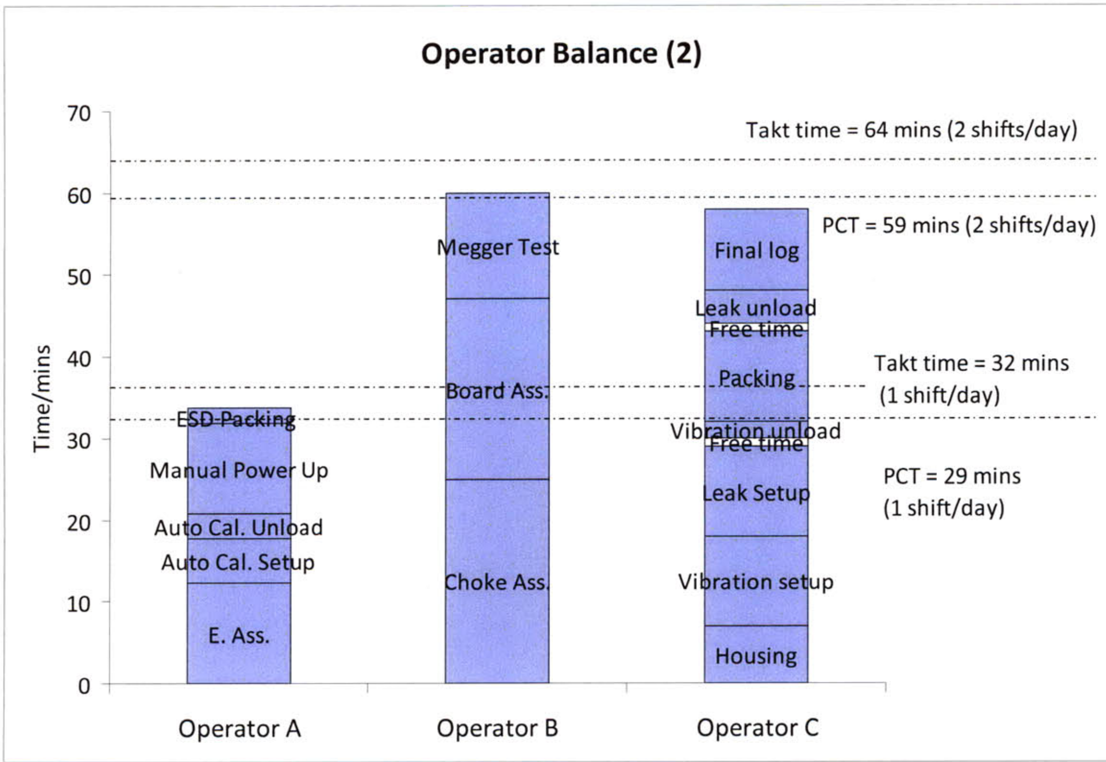

Figure 5-6 Operator workload balance for XT – option 2

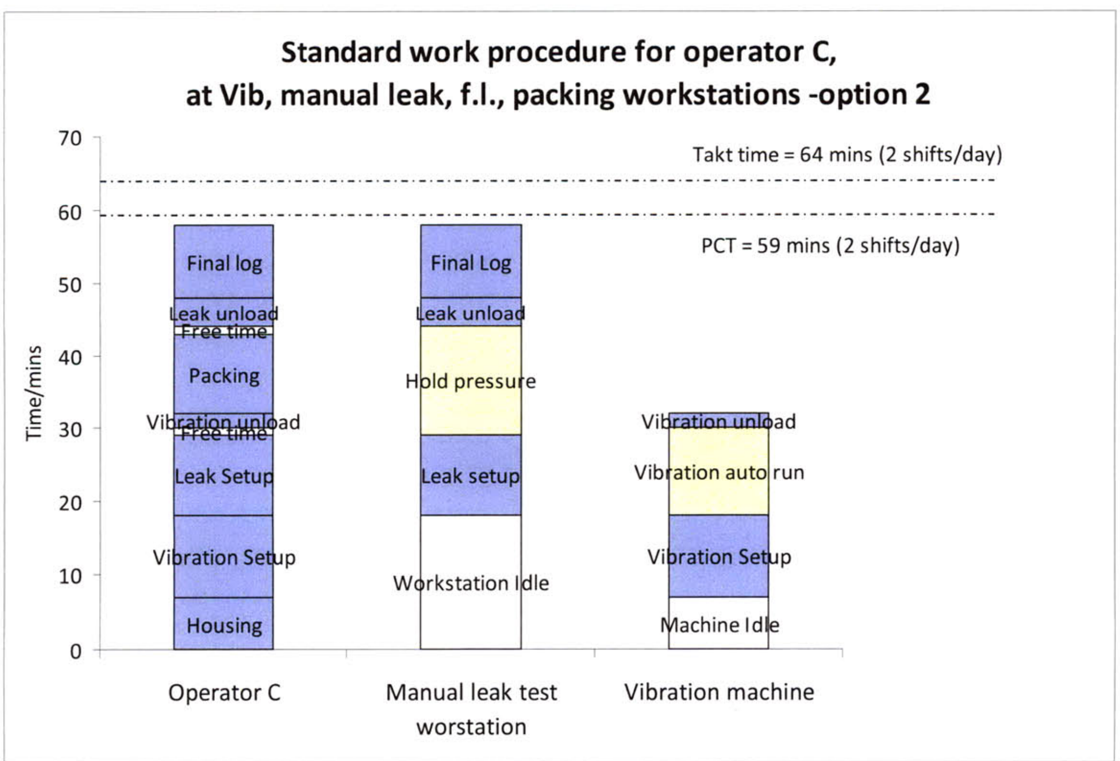

Figure 5-7 Standard work procedure for operator C for option 2

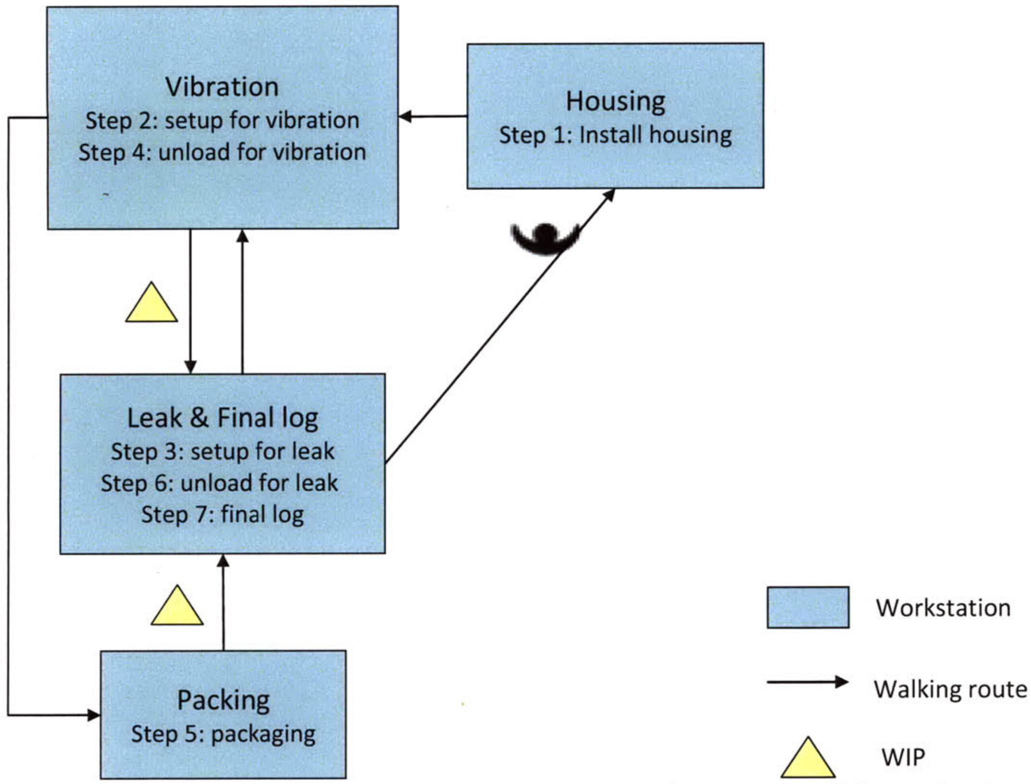

Figure 5-8 Flow chart of standard work procedure for operator C for option 2

The test results could be checked immediately after the tests are done. Moreover, the design facilitates the continuous flow from housing to vibration and eliminates the WIP between housing stand and vibration test station. However, there is more walking required. Machine reliability requirement is high. And the workload is heavy for a single operator and the ergonomics problem remains. To counter these problems, option 3 is provided.

Option 3

Option 3 is designed to meet the demand and at the same time to achieve easier and safer job for operators. Figure 5-9 shows the operator workload balance chart option 3. There are totally four operators in the production line. Operator A and B take the same responsibilities as in option 1 and 2. However, two operators instead of one take charge from housing to packing workstations. The flow chart for operator C and D according to the standard work procedure is shown in Figure 5-10. Operator C takes charge of housing and vibration test. He could actually install the housing for one gauge while vibration test is auto running, since the machine running time is longer than the time needed for installing housing. Operator D takes charge of leak test, final log and packing. Similarly to operator C, he could pack the gauge while the leak test station is holding pressure for testing. As shown in figure 5-9, the cycle time for operator C is 25 minutes, which is 4 minutes below the PCT and 7 minutes below the Takt time with 1 shift per day. So operator C is expected to finish his job about 1 hour before the end of the shift and he could move on to do other tasks. The total cycle time for operator D is 40 minutes, which is 8 minutes beyond the Takt time and 11 minutes beyond the PCT with 1 shift per day. Therefore, operator D is expected to finish his daily tasks with 1 shift and 2.5-hours OT. The unbalanced workload assignment between operator C and D requires a FIFO lane established between vibration test workstation and manual leak test/final log workstation. The numbers of gauges coming out from vibration test, sitting in the FIFO lane and packed within a morning shift is summarized in Table 5-2.

Although the operator workload is not really balanced for option 3, it has several advantages, e.g. it provides easier job for operators thus easier to implement; if there are two operators working at the mechanical assembly workstation, 1 shift could be dedicated to product family A production and produce to demand. The 2nd shift can work for special orders and catching up backlogs.

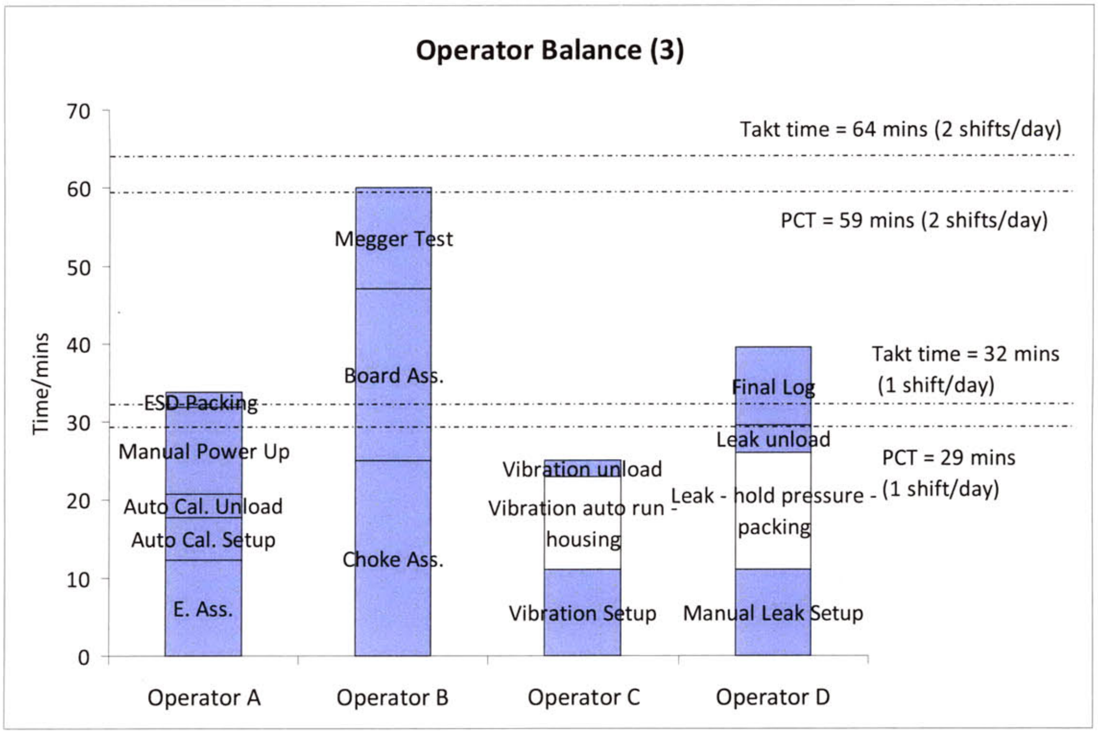

Figure 5-9 Operator workload balance for XT – option 3

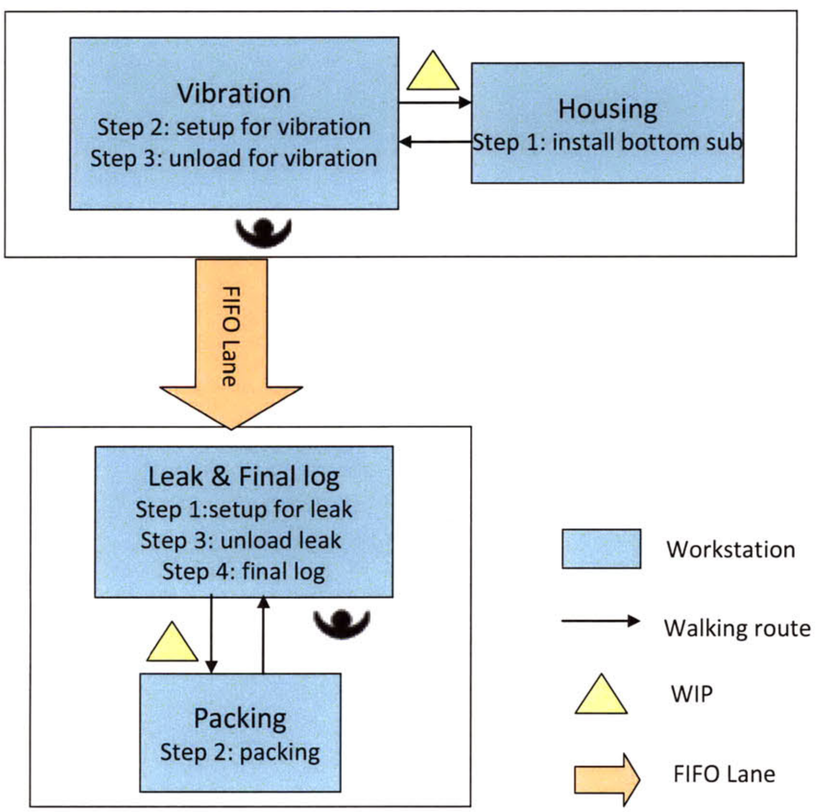

Figure 5-10 Flow chart of standard work procedure for operator C and D for option 3

Table 5-2 Detailed pitch and WIP plannin for option 3

Time	Operator C	Operator D	Vibrated gauge	FIFO lane	Finished Goods
7:30am	Vibration table warm-up	Leak preparation	-	1	-
7:40am	Setup vib for 1st	Setup leak for 1st	-	0	-
8:05am	Setup vib for 2nd		1	1	-
8:20am		Setup leak for 2nd	-	0	1
8:30am	Setup vib for 3rd		2	1	-
8:55am	Setup vib for 4th		3	2	-
9:00am		Setup leak for 3rd	-	1	2
9:20am	Setup vib for 5th		4	2	-
9:40am		Tea break till 9:55am	-	2	3
9:45am	Tea break till 10am		5	3	-
9:55am		Setup leak for 4th	-	2	-
10:00am	Setup vib for 6th		-	2	-
10:25am	Setup vib for 7th		6	3	-
10:35am		Setup leak for 5th	-	2	4
10:50am	Setup vib for 8th		7	3	-
11:15am	Setup vib for 9th	Setup leak for 6th	8	3	5
11:40am	Setup vib for 10th		9	4	-
11:55pm		Lunch break till 12:25pm	-	4	6
12:05pm	Lunch break till 12:35pm		10	5	-
12:25pm		Setup leak for 7th	-	4	-
12:35pm	Setup vib for 11th		-	4	-
1:00pm	Setup vib for 12th		11	5	-
1:05pm		Setup leak for 8th	-	4	7
1:25pm	Setup vib for 13th		12	5	-
1:45pm		Setup leak for 9th		4	8
1:50pm	Finished		13	5	-
2:25pm		Tea break till 2:40pm	-	5	9
2:40pm		Setup leak for 10th	-	4	-
3:20pm		Setup leak for 11th	-	3	10
4:00pm		Setup leak for 12th	-	2	11
4:40pm		Setup leak for 13th	-	1	12
5:20pm		Finished	-	1	13

Trial run result and implementation plan

Three options were tried out by the production line. Operators worked according to the established standard work procedure and were kept out of interruptions. For option 1 and 2, the finished goods output per shift were 6 and 7 pieces, respectively. While for option 3, the operator C taking charge of housing and vibration finished the work for 13 pieces of gauges at 2:00pm, which is 1.5 hours before the 1^{st} shift ends; the finished goods output after the 1^{st} shift ends was 10 pieces; and with 2-hours OT, the operator D produced totally 13 pieces of gauges. However, the operators running for option 1 and 2 reported fatigue after the trial runs. During the trial runs, the instability of the leak test workstation was noticed. The operators need to constantly check the stability of the pressure and adjust the connectors to prevent leak. For option 1 and 2, the adjustment was sometimes delayed since the operators need immediately work at vibration or packing stations after leak is setup. On the other side, since the time needed for packing is less than the pressure holding time for leak test, option 3 allows operator D to adjust the connectors after the leak test is set up. Considering other advantages of option 3 mentioned in previous part too, the current production line decided to implement option 3 for current operation. After improving the reliability of the leak test workstation, e.g. redesigning the fixture or changing the connectors, and solving the ergonomics problems, e.g. redesigning the floor layout to shorten walking distance and designing special trolley to carry and load the gauge, option 1 and 2 could be considered for implementation.

To implement option 3, the standard work procedure/flow chart for each operator is pasted on the wall nearest to them. The standard work procedure with photos for each workstation/process is also placed at the workstation for reference.

As the gauge may fail for vibration test or leak test, 1 buffer stock is added to the FIFO lane and the WIP between leak test workstation and packing station respectively to allow continuous flow of the processes. The failed parts are returned to the RON area and are inspected and reworked after finishing one day's work.

Also, a FIFO lane with maximum size of 5 has been designed. There are 5 green boxes drawn on the floor. There is a yellow box with a gauge sitting on it. This gauge can only be used when a failure occurs at the vibration station. There is a similar yellow box between leak test workstation and packing station. The gauge sitting in the yellow box can only be used when a failure occurs for leak test. And for the FIFO lane, there is a 7th red box to alarm the nonconformance to standard production. A green card is placed with the next gauge to run leak test according to the sequence of the vibration test done. Score boards to record the number of gauges completed are placed at the vibration station and packing area respectively.

Discussion for other products in product family A

The current production order is to produce single product type in one day. Therefore, the workload balance can be discussed separately for different products. The previous work is based on the high runner product A's timing. Since the timing of product C is the same as product A's timing, the production planning has no difference. However there are variations in timing of some of the workstations for product B. Thus the workload balance for product B needs to be discussed.

The major differences in timing are for mechanical assembly and vibration test. The total cycle time of mechanical assembly for product B is 90 minutes, and the total cycle time of vibration test for product B is 40 minutes. Thus assuming the production line plan to produce to demand using 1 shift per day, the operator workload balance is similar to option 3 of product A's production. However, the production line needs 3 operators working on the mechanical assembly workstation. And the vibration station workload is balanced with the leak test/final log workstation. There is minimal WIP between these two workstations.

5.3 Future State Mixed Model Value Stream

5.3.1 Equipment support analysis for 2011

Assuming the cycle times for equipments don't change, the up time for equipments can achieve the target of 95%, and the failure rate for auto calibration can improve to 6.25% in 2011, the equipments needed are calculated and summarized in Table 5-3. The number of equipment needed for auto calibration machine is larger than 1. As there are two auto calibration machines available in the production line and cycle time for auto calibration is expected to be further reduced, auto calibration machines can support the production in 2011. Packing station also has enough capacity. However, the vibration test station is approaching the limit of the capacity. And the number of manual leak/ final log workstation needed is larger than 1. As vibration station and leak test/final log workstation are shared resources with other product families, new designs of the processes or additional equipments are needed for the vibration test and leak test/final log.

Table 5-3 Equipment needed for product family A production in 2010

Equipment	Sum (C/T x Demand) (mins)	Up time	Defect rate	Effective working time (mins)	Equipment needed
Auto calibration	312391.25	95%	6.25%	345600	1.014916342
Vibration test	165850	95%	1%	201600	0.874714142
Manual Leak + Final log	240880	95%	1.50%	201600	1.276880865
Packing	70162	95%	0%	201600	0.366342941

5.3.2 Future State process flow

The process flow is expected to be improved and resulted as shown in Figure 5-11. Comparing Figure 5-12 with Figure 1-5, the major changes in process flow are: kitting processes are added for electronics parts and mechanical parts respectively to eliminate waste of time in looking for parts during production, to enable mistake-proof in production, and to facilitate the continuous production (more information on kitting is discussed in Ren's work [11]); the manual calibration is removed as the reliability of the auto calibration machine improves; furthermore, in order to expand the capacity of the vibration station and shorten the customer lead time, the vibration workstation is to be moved after the auto calibration test and to be conducted in batch of 16 for the PCBs; moreover, to expand the capacity for leak test and final log, the auto leak test machine is expected to replace the manual leak test machine and conduct leak test and final log within one setup for two gauges each time; also, considering the ergonomics problem in manual housing assembly process, the housing process is designed to be automatic; and the curing time is to be reduced from 2 days to 1 day. In addition, bar coding is to be implemented in the processes to facilitate the production as well as to track the parts. These projects are covered by engineers of the production line and many projects have impact on the cycle time of the processes.

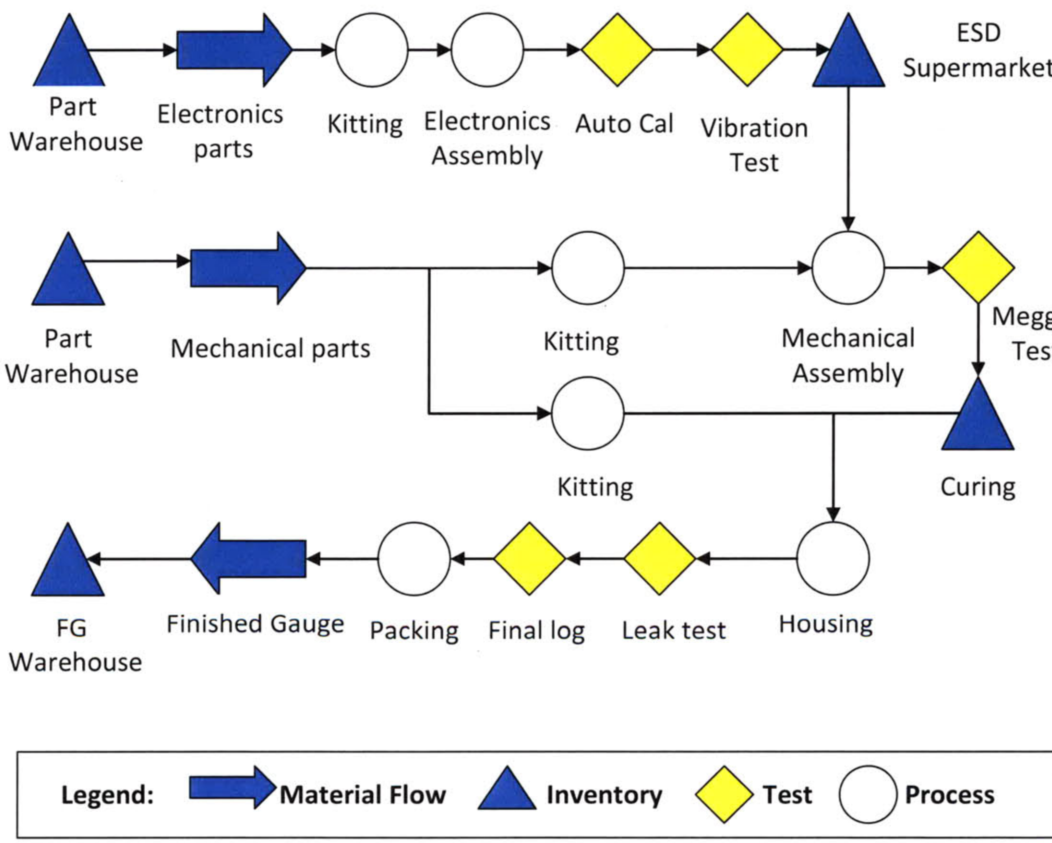

Figure 5-11 Process flow of gauge production

The estimated/targeted new cycle time for each process after the improvements is shown in Table 5-4 to Table 5-6 below. In 2011, the new product A model A-d is expected to replace the A-0 and A-1 products. The A-d product is expected to need more time in both electronics and mechanical assembly than product A-0 and product A-1.

Table 5-4 Targeted cycle time for workstations (product A-d)

Work Element	Batch size	Time Element (mins)	
		Manual	Auto
Electronics Kitting	16	25	
Electronics Assembly	16	144	
Auto Cal Setup	16	56	
Auto Cal Auto Run	16		720
Auto Cal Unload	16	44	
Vibration Setup	16	40	
Vibration Auto Run	16		15
Vibration unload	16	32	
ESD Packing	16	15	
Gauge Assembly kitting	1	3	
housing & packing kitting	1	3	
Gauge Assembly	1	52	
Housing	1	6	
Auto leak/final log setup	2	5	
Leak/final log auto run	2		40
Auto leak/final log unload	2	7	
Packaging	1	8	

Table 5-5 Targeted cycle time for workstations (product C)

Work Element	Batch size	Time Element (mins)	
		Manual	Auto
Electronics Kitting	16	25	
Electronics Assembly	16	120	
Auto Cal Setup	16	56	
Auto Cal Auto Run	16		720
Auto Cal Unload	16	44	
Vibration Setup	16	40	
Vibration Auto Run	16		15
Vibration Unload	16	32	
ESD Packing	16	15	
Gauge Assembly Kitting	1	2	
Housing & Packing Kitting	1	3	
Gauge Assembly	1	44	
Housing	1	6	
Auto Leak/Final Log Setup	1	5	
Leak/Final Log Auto Run	1		40
Auto Leak/Final Log Unload	1	7	
Packaging	1	8	

Table 5-6 Targeted cycle time for workstations (product B)

Work Element	Batch size	Time Element (mins)	
		Manual	Auto
Electronics Kitting	16	25	
Electronics Assembly	16	144	
Auto Cal Setup	16	56	
Auto Cal Auto Run	16		720
Auto Cal Unload	16	44	
Vibration Setup	16	40	
Vibration Auto Run	16		15
Vibration Unload	16	32	
ESD Packing	16	15	
Gauge Assembly Kitting	1	3	
Housing & Packing Kitting	1	3	
Gauge Assembly	1	60	
Housing	1	6	
Auto Leak/Final Log Setup	1	5	
Leak/Final Log Auto Run	1		40
Auto Leak/Final Log Unload	1	7	
Packaging	1	8	

5.3.3 Future State operator workload balance

Operator workload is balanced according to the new Takt time and the new flow. The resulted balance charts for products A-d, B and C are shown in Figure 5-12 to 5-14 below. Generally speaking, there are two shifts for each day's production and four operators are needed for each shift to meet future state demand. The first operator takes charge of the work until ESD supermarket. As the work is in batch of 16, the effective working time for 1 gauge is shown in the figures. The time is well below the planned cycle time. The operator is high level technician, thus he is also expected to coordinate and monitor the production line all the time.

Then operator B and C work on the gauge assembly workstation. They can either break down the assembly work to two parts or work in parallel. Notice that product C requires only 22 minutes for each operator; while product A-d requires 26 minutes and product B requires the longest time – 30 minutes. In a mixed model production, the longer time required for one product could be absorbed by the shorter time needed for another product. In this case, the average cycle time of the three products for each operator is 26 minutes, which is 3 minutes below the planned cycle time. And the 3 minutes per cycle are used for preparing the kits for assembly.

Finally, operator D works for housing, leak test and packing. Since the leak test is conducted for two gauges for each run, the effective setup, run, and unloading time for one gauge is used in the balance chart. As shown in the figure, the effective cycle time for one gauge is 27 minutes, which is 2 minutes below the planned cycle time. The operator utilizes the machine running time to do the packing and housing. And the remained 2 minutes per cycle are used for preparing the kits for housing to packing.

The pitch for finished goods is set as 0.5 hour for monitoring the production.

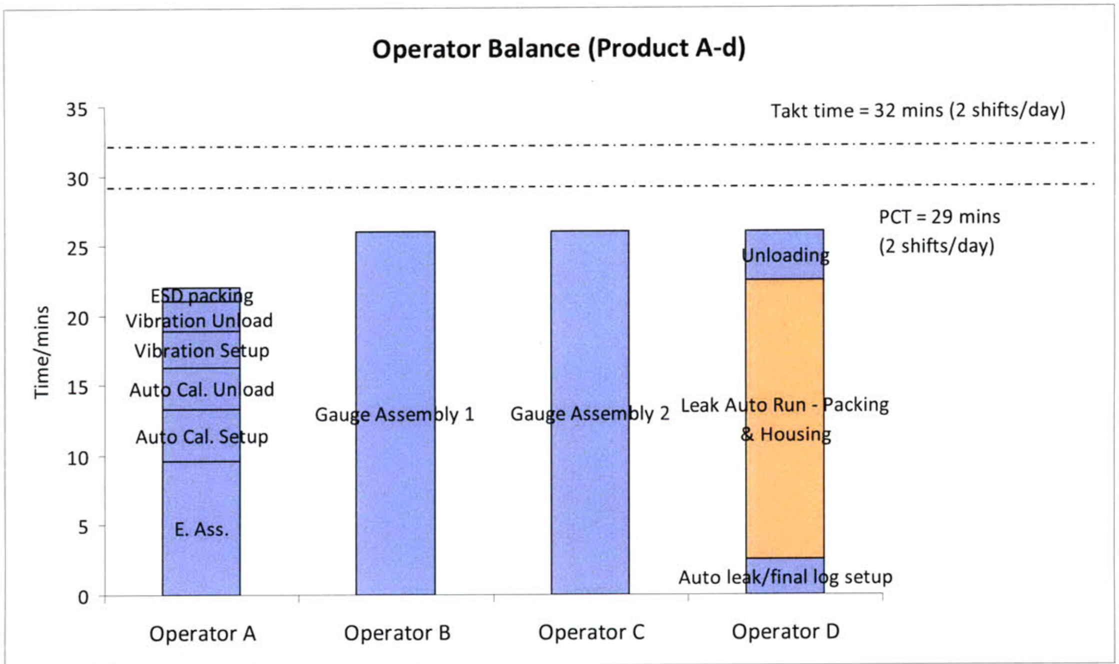

Figure 5-12 Operator workload balance for product A-d (2011)

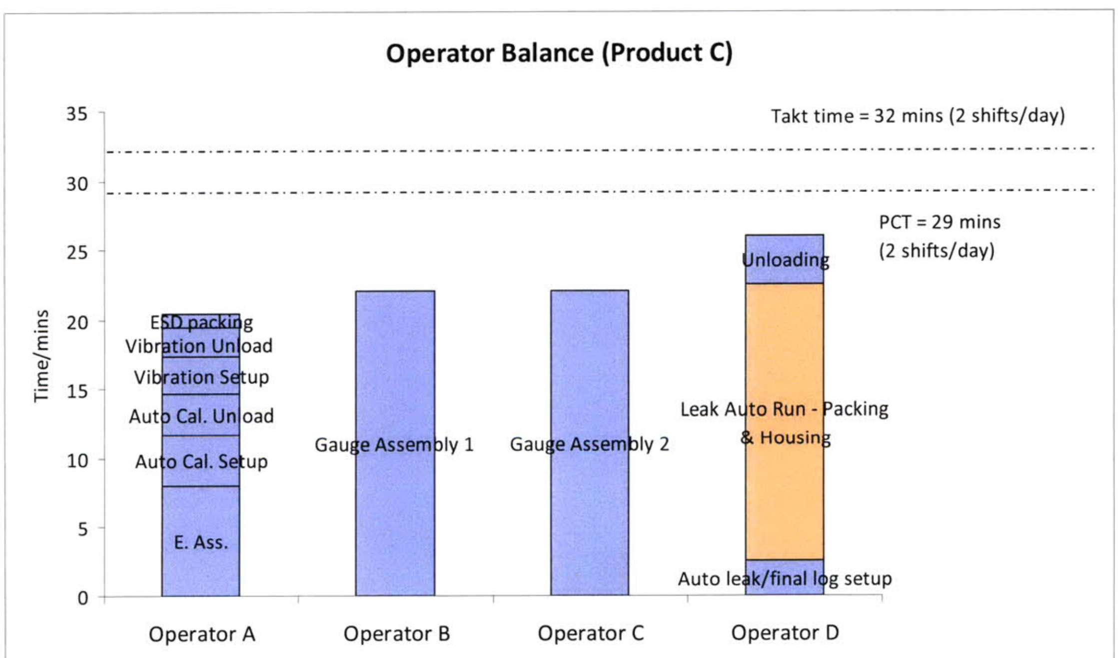

Figure 5-13 Operator workload balance for product C (2011)

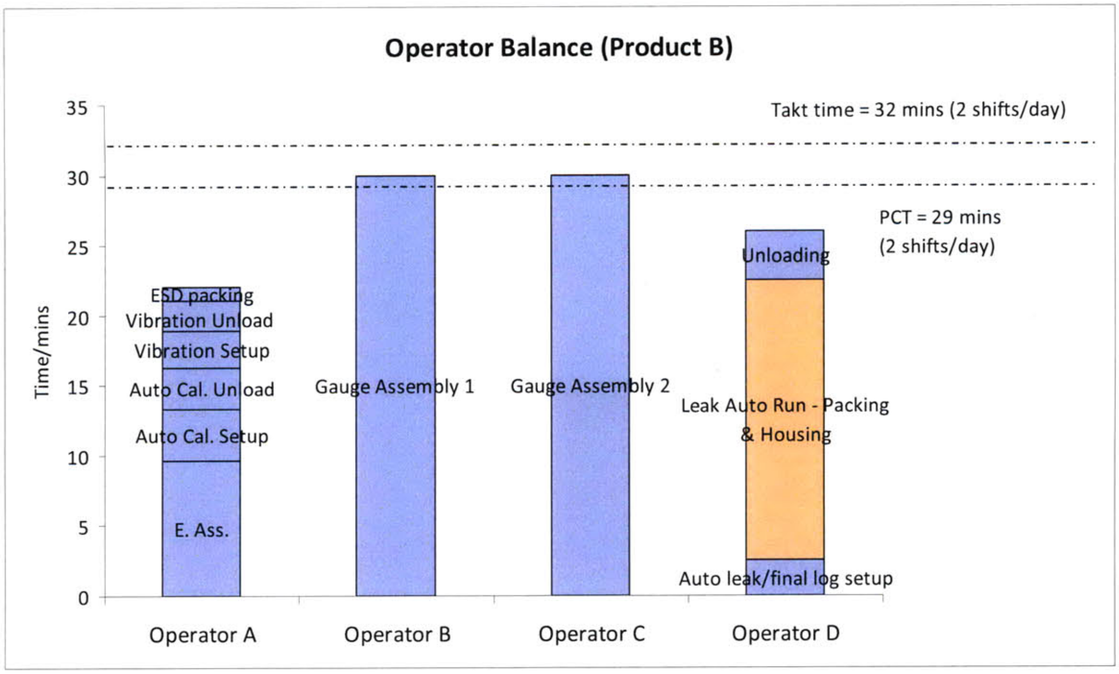

Figure 5-14 Operator workload balance for product B (2011)

5.3.4 Future State production strategy

As the production line expects to have relatively steady demand for the high runner product A-d, it is recommended to build a finished-goods supermarket for product A-d. The safety stock in the supermarket is expected to accommodate the variation in demand for the product A-d. The forecast demand is updated frequently to adjust the level of the supermarket. Although product C has a relatively low demand, it is expected to have relatively steady demand. So finished goods supermarket is decided to be the finished goods strategy. So, customers could pull product A-d and C from the finished goods inventory with minimal lead time. On the other hand, make-to-order strategy is to be implemented for product C, which has least demand in 2011 and also has high monthly demand variation. By combining the make-to-stock and make-to-order strategy, the inventory level of finished goods is relatively low but the production line could still meet a short lead time to customer.

To further improve the customer service level, reduce the lead time to customers, and have better control in the production line, Kanban system is suggested to be established in the production line. The number of Kanban cards for products A-d and C is the same as the supermarket size and it is planned according to forecast demand. The Kanban system is discussed in detail below.

To achieve the shortest lead time, the pacemaker or the direct point initiating production by Kanban is after the curing stage, which is the housing station. Therefore, after the gauges have been pulled from the finished goods supermarket by customers, production Kanban is issued to the housing workstation everyday. Then the housing workstation pulls gauges and kits from the supermarkets and initiates production to replenish the finished goods supermarket. The process of the 1st Kanban loop is depicted in Figure 5-15.

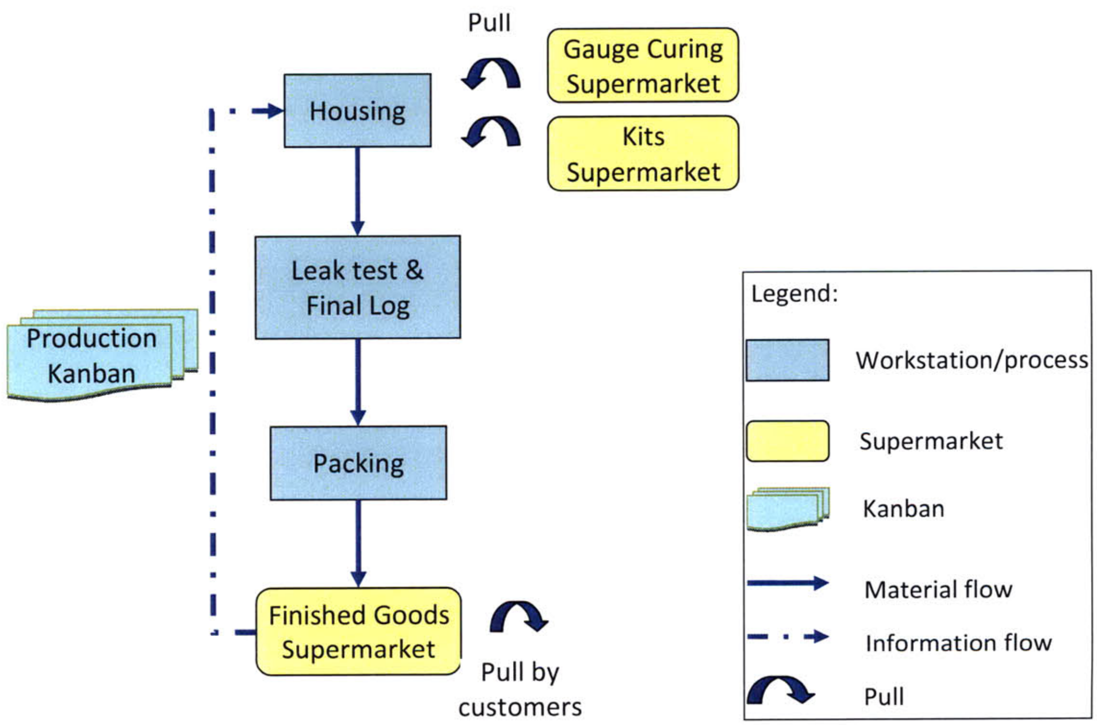

Figure 5-15 Kanban system from housing to finished goods supermarket

The second Kanban loop is from mechanical assembly workstation to curing. As gauges are pulled from the curing supermarkets, the supermarket inventory level drops and the second Kanban is returned to mechanical assembly workstation to initiate daily production. The process is shown in Figure 5-16.

Similarly, the third Kanban loop is from electronics assembly to ESD supermarket as shown in Figure 5-17. As PCBs are pulled from the ESD supermarket, the Kanban is returned to the electronics assembly workstation to initiate production. However, as batch production is required for this loop, a batch production Kanban system which only initiates the production when the ESD supermarket drops to certain level is desired.

Finally, kits supermarkets are also replenished after they have been pulled by production as shown in Figure 5-18. The Kanban levels will be determined and discussed later.

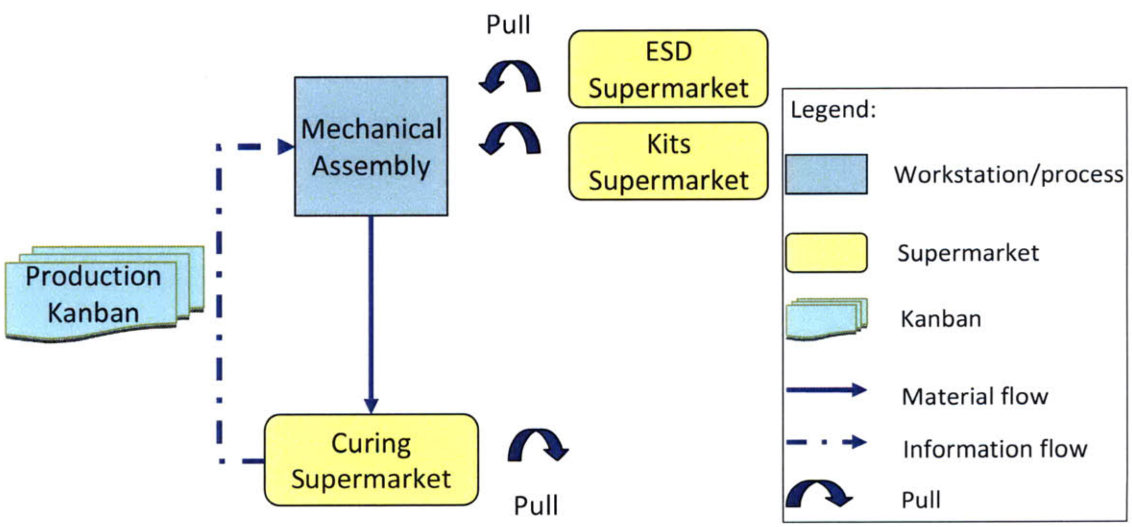

Figure 5-16 Kanban system from mechanical assembly to curing

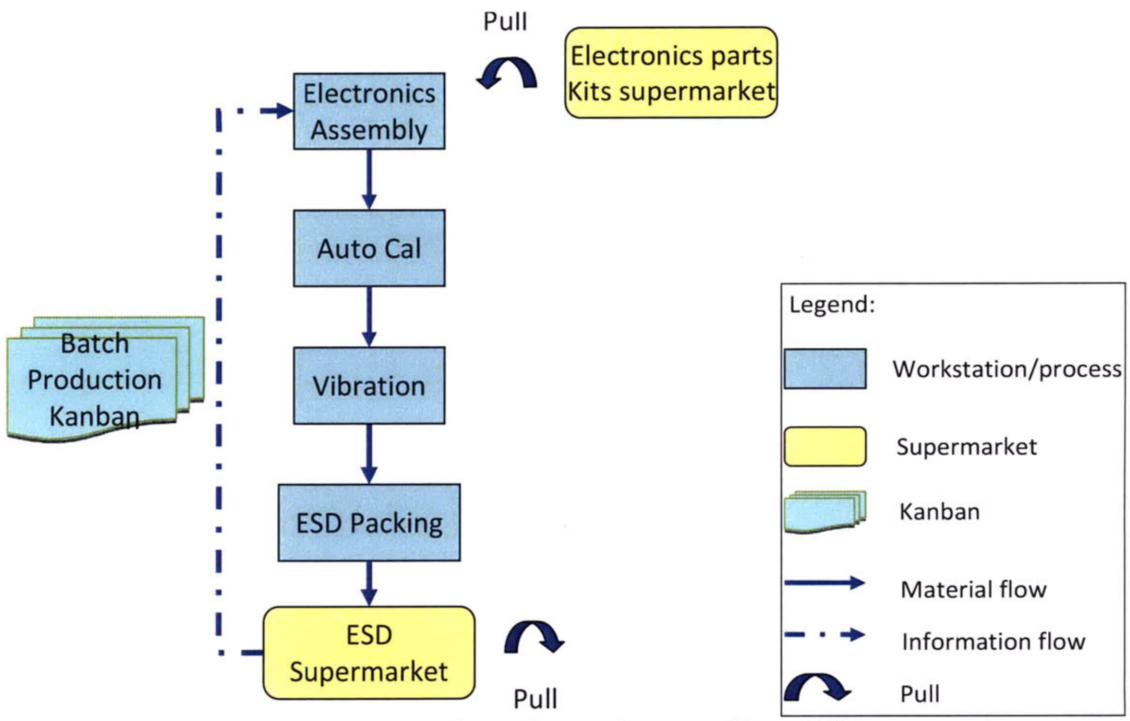

Figure 5-17 Kanban system from electronics assembly to ESD supermarket

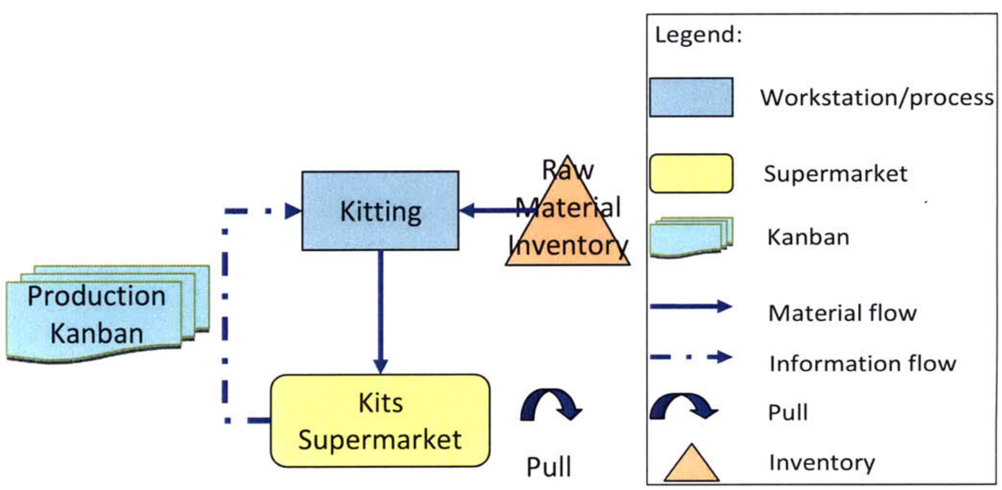

Figure 5-18 Kanban system for kitting

Similarly, for the make-to-order product C, when order comes, the order is released at the finished goods inventory, and the production Kanban is issued to the pacemaker- housing station by mixing with the production Kanban of products A-d and C. At the same time, a 1-day's offset order is released in advance for preparing kits and the mechanical assembly workstation. The supervisor is then expected to level the daily schedule for mixed production. On the other hand, ESD supermarket is also needed for product B, as each order is expected much smaller than the production batch size for the PCBs.

5.3.5 Supermarket Sizing

A simple assumption has been applied on the forecast demand data for illustration purpose. The yearly demand forecast for product A in 2011 is 2.18 times of the demand forecast in 2012, and the yearly demand for product C in 2011 is 2 times of the demand forecast in 2012 as revealed in the forecast data shown in Table 4-5 and 4-7. Thus it is assumed that the demand of every day in 2011 is 2.18 times or 2 times of the everyday's demand in 2010. As only the demand data from Jan to June 2010 is available now, the predication on forecast is only from Jan to June 2011. Also, as there are only monthly demand recorded in the system, the daily demand variation is calculated by dividing the monthly variation by number of working days per month (20 days), assuming the daily demand is independent. The forecast demand data for Gauge yields the daily average demand and demand variation as shown in Table 5-7 below. More accurate forecast data is required to effectively monitor and adjust the supermarket level and ensure the fulfillment of customer demand. Therefore, a project on improving forecast demand accuracy is proposed and will be conducted in the next 4 months. As a project on improving demand pattern is also in process for the production line, the real demand is expected to have lower variation than tabulated here.

Table 5-7 Forecast demand in 2011

Forecast Demand 2011	A	B	C
Average Monthly Demand	456	4	46
Average Daily Demand	22.8	0.2	2.3
Monthly Standard Deviation	40	1.9	11.8
Daily Standard Deviation	9	0.42	2

Assuming the demands in non-overlapping time intervals are independent and the demand for different products are all normally distributed, the size of finished goods supermarket, curing supermarket, and the kits supermarket are calculated using the periodic review model. And the size for ESD supermarket is calculated using the continuous review model. The calculated supermarket level according to 98% customer service level, respective lead time, review period and demand data has been tabulated in Table 5-8 below. As shown in the table, since the finished goods are only pulled and shipped once per day, the review period for finished goods inventory is to be set at least 1 day. And to minimize the supermarket size, a review period of 1 day is used. The review period for curing is set as 0.5 day or 1 shift. And the kits are to be prepared at the end of each day to replenish to base stock level. The base stock level is the starting stock level as well as the number of Kanban cards for the system. The production line is expected to order the amount equal to the consumption since last replenishment epoch for finished goods, gauges sitting for curing and the kits. And for ESD supermarket, the operator is expected to prepare a new batch when the number of PCBs drops to the reorder point.

Table 5-8 Supermarket size in 2011

Supermarket Size		Lead Time	Review Period (day)	Order Quantity	Safety Factor	Cycle Stock	Safety Stock	Expected Inventory Level	Base Stock	Reorder Point
A	F.G.	0.5 hr	1	N.A.	2	11	18	29	41	N.A.
	Curing	1 day	0.5	N.A.	2	6	22	28	56	N.A.
	Kits	1 hour	1	N.A.	2	11	18	29	41	N.A.
	ESD	1 day	N.A.	15	2	8	18	26	N.A.	41
C	F.G.	0.5 hr	1	1 day	2	1	4	5	6	N.A.
	Curing	1 day	0.5	0.5 day	2	1	5	6	8	N.A.
	Kits	1 hour	1	1 day	2	1	4	5	6	N.A.
	ESD	1 day	N.A.	15	2	8	4	12	N.A.	6
B	ESD	1 day	1	15	2	8	1	9	N.A.	2

5.3.6 Schedule for the mixed production

The production line produces to replenish the finished goods supermarket as well as to fulfill the order for product B from the customer. Although the daily demand may vary from day to day, in short term, by implementing the finished goods supermarket strategy, the production line is expected to have relatively steady daily production throughput. Assuming the overall demand is normal distributed, when a trough of demand comes, the company will expect a rise of demand very soon. So when demand is low, the production line should produce to build to stock and get ready for the rise of demand. Then when the demand rise comes, the production is ready to meet the demand with the stock built. Operator can work with slight OT to accommodate the small variations in demand.

In long term run, the company may face a jump or drop in demand considering the overall market and economic situation. Then, the capacity planning need be re-evaluated. Equipment may need re-engineering or new acquisition. And operator may be added or subtracted. Shift may also be redesigned.

In short term run, although the production throughput is relatively steady, the mix for daily production may vary and the production line need determine the rules and logic for scheduling for mix. For example, in a particular day, an order for 4 product B gauges comes in; at the same time, there are 20 Kanbans for production of product A-d and 2 Kanbans for production of product C. The production line should work for make-to-order product first as the earlier these gauges are built, the faster the customer can receive the gauge. On the other hand, the make-to-stock products can be pulled by customer any time they want to. Then the daily production Kanban is placed and sequenced on the scheduling board for visualization. An example is shown in Figure 5-19 below. The operator working for housing picks one Kanban at a time and the Kanban goes with gauge till it's pulled by the customer. At the end of the day, the supervisor of the production line collects the cards from the finished goods inventory and begins arrange for tomorrow's production. A similar Kanban/scheduling board is place at the mechanical assembly workstation. However, different products take different time for mechanical assembly. As the time scale doe not change on the board, the Kanban card height for different products is designed to the scale of time spent for process.

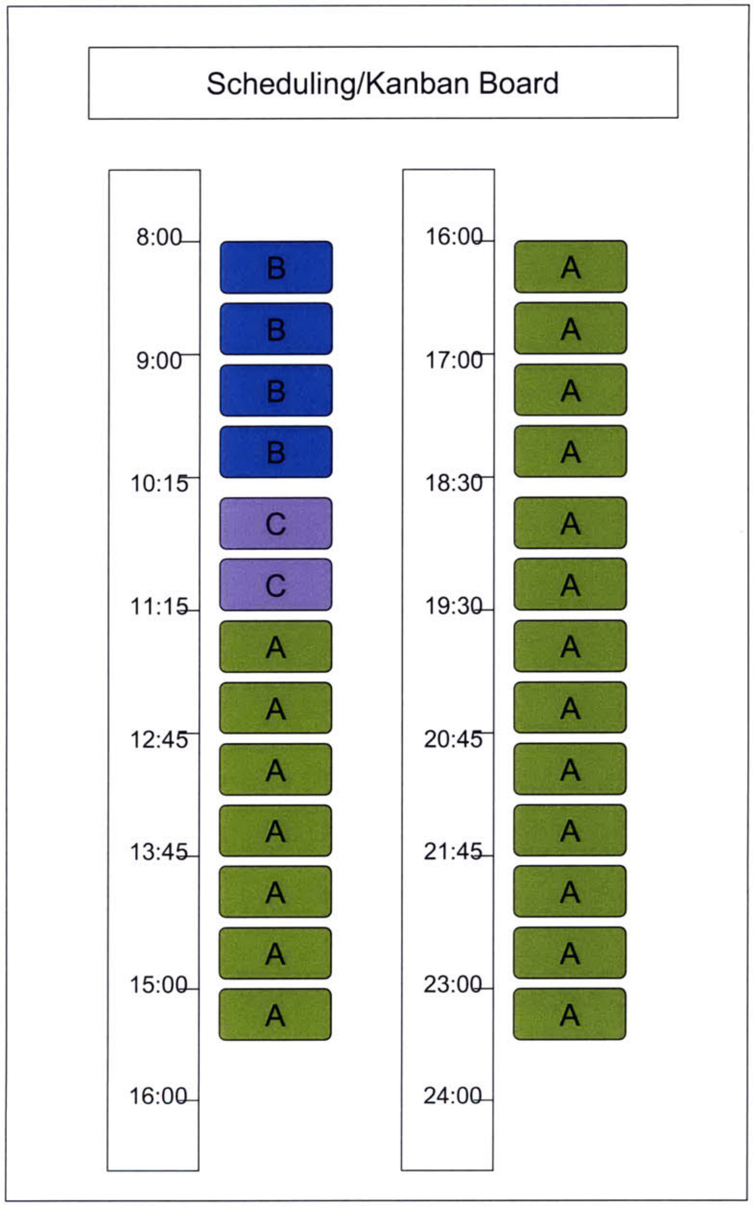

Figure 5-19 Scheduling Board at Housing

5.3.7 Future State Value Stream Map

The future state value stream map is shown in Figure 5-20 according to the results from section 5.3.1 to 5.3.7. The total lead time for electronics parts from receiving to ESD supermarket is reduced from 89 days to 48 days. At the same time, the total process time for a batch of electronic parts to ESD supermarket is reduced from 21 hours to 17 hours. Furthermore, the total lead time for electronics parts and mechanical parts from receiving to shipping is reduced from 100 days to 51 days and 57 days to 31 days respectively. And the total process time for one gauge is about reduced from 4.1 hours with 2 days for curing to 2.5 hours with 1 day for curing.

In summary, to reach the future state, the major projects include: reduce supplier lead time from 9 months to 3 months for electronics parts; control the inventory level needed for 1 month production for mechanical parts; inspection is conducted right after receiving to allow faster reaction to quality issues, and selective examination is expected to replace the 100% inspection as the reliability of supplier is expected to be improved; kitting is designed to facilitate the production and mistake-proof; up time and pass rate of auto calibration is improved from 90% to 95% and 81.25% to 93.75% respectively; vibration is conducted in batch of 16 for PCBs; leak test and final log is conducted in one setup for 2 gauges; bar coding for tracking parts and test results recording is implemented; Kanban system is established as discussed.

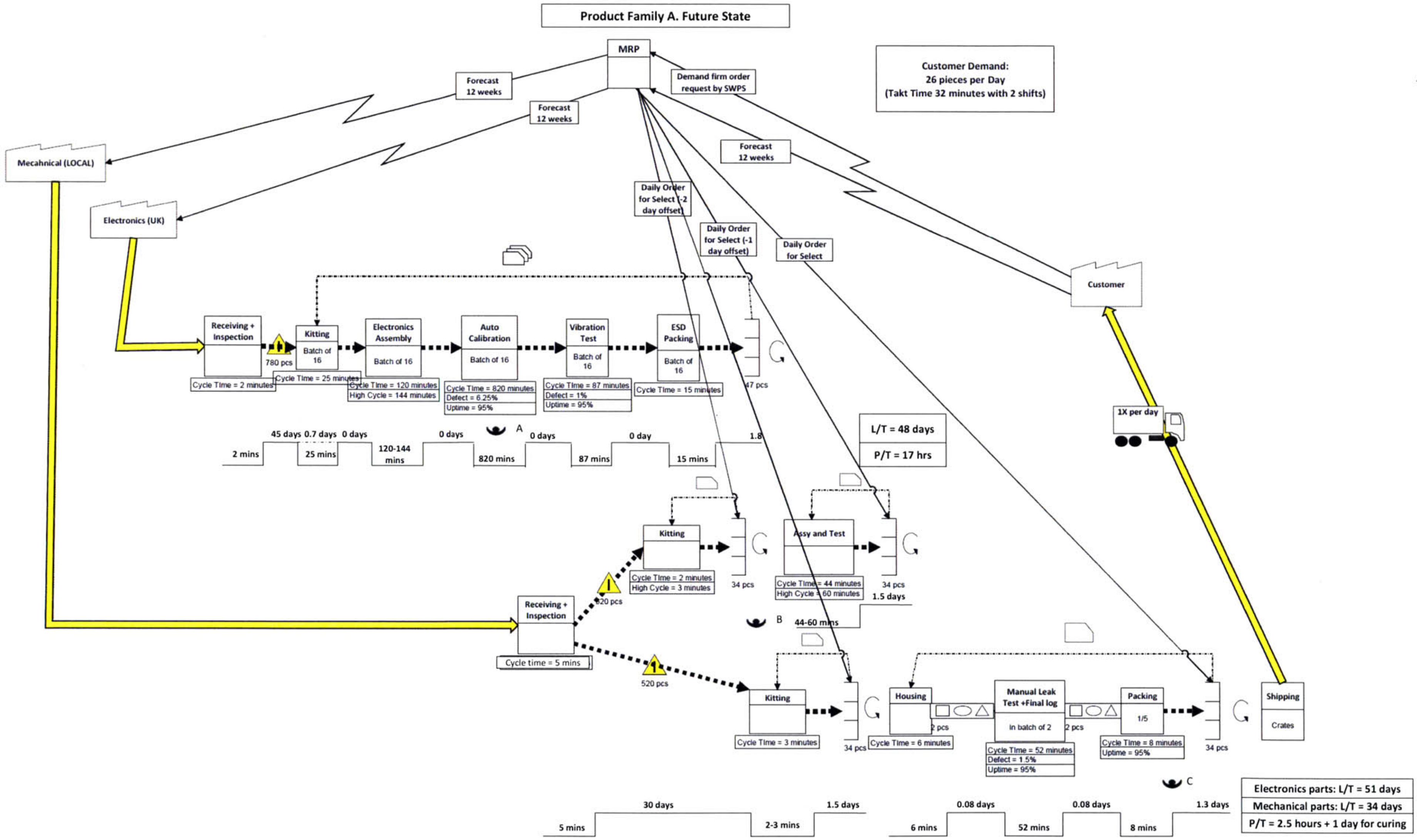

Figure 5-20 Future State Value Stream Map 2011

Chapter 6 Recommendations

The company is recommended to immediately implement the operator workload balance and standard operator work procedure to produce to current demand.

The company should also work on the continuous improvement projects for processes and supply chain; the new operator workload balance and standardized work procedure should be implemented once the new process is ready to meet the doubling demand; the production line need also establish the Kanban and mixed scheduling system to eventually realize the future state production.

In particular, the implementation of Kanban system is a continuous process with several milestones to be achieved. Firstly, the company is suggested to let the operator in the company understand and get familiar with the system by trying the Kanban system for the high runner, product A under current planning system (refer to Junying's work [12]). A finished goods supermarket is to be built inside the production line with a stock level of 13 pieces. The planner releases 13-pieces' order for product A production everyday and pulls 13 pieces from the finished goods supermarket after each day's production. The Kanban level depends only on the cycle stock level. After successful trial, Kanban for products B and C will be added in for mixed production. The planner still promises lead time to customers and releases order to the production line. When there is no variation in daily mix combination, the Kanban level is determined only by cycle stock level too. However, if the planner starts varying the combination of products from day to day, buffer level for Kanban will be added in. The planner can eventually shorten the lead time to customers. Finally, only after the demand pattern is structured steadily, the demand is forecasted more accurately, and all backlogs are cleared up, customer can pull from the finished goods supermarket directly.

Chapter 7 Conclusion and Future Work

The current daily throughput of the production line is 10 gauges. However, the average daily demand is 13 gauges now. Moreover, the production line is facing doubling demand next year. Thus, to help the company remain competitive in the market, this project aims to improve the current operation of the production line to build to current demand, as well as to create a mixed production value stream to prepare for the future state rocketing demand.

The project focused on the high runner product family A. The project was carried out by firstly collecting data for the current production line and constructing the current state value stream. The problem of un-standardized work in the production line was noticed. And to design the standard work procedure for operators, the operator workload was balanced to achieve the current demand rate. The daily production throughput increased by 30% from 10 gauges to 13 gauges. At the same time, monitoring techniques for production control was implemented to facilitate the implementation of standardized operation.

Then, the necessary changes for the production line were identified by analyzing the capacity need for future production, as well as by discussing with the engineers about the ongoing process improvement projects. The new flow and cycle time were used for operator workload balancing, establishing make-to-stock production strategy for higher runner product A and C, establishing make-to-order production strategy for product B, and developing the new production control system: Kanban system. The daily production rate was expected to meet the average demand of 26 gauges per day. And the daily production was expected to mix the products A, B and C to allow shortest lead time for all products.

Finally, the future state value stream map was constructed. As the demand doubles for the future state, the total lead time for electronics parts from receiving to ESD supermarket was reduced from 89 days to 48 days. At the same time, the total process time for a batch of electronic parts to ESD supermarket was reduced from 21 hours to 17 hours.

Furthermore, the total lead time for electronics parts and mechanical parts from receiving to shipping was reduced from 100 days to 51 days and 57 days to 31 days respectively.

This study is based on the assumption that all the resources mentioned are dedicated to the product family A. However, some of the resources, especially the equipments are shared with other products. The influence of other product family needs be considered and analyzed in future work. Also, at the current stage, while implementing the Kanban system, instead of letting customers directly pull from the finished goods supermarket, the planner still needs promise the due dates to customers and release the order to the production line. The logic for the planner to schedule and mix the daily production need to be studied and standardized. Eventually, as the demand pattern is structured steadily, the demand is forecasted more accurately, and all backlogs are cleared up, customer can pull from the finished goods supermarket directly.

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APPENDIX

Time study worksheet

Standardized Worksheet		**Process: AutoTest**			Procedure #	Rev.
					Date:	
					Page 1 of 1	
Plant Name	**SPE**	**Department**	**Monitoring Lab**	Tools and Materials:		
Takt Time	**mins**	**Part Number**		Parts:		
Cycle Time	**mins**			Safety Equipment:		
Approved By:	Lead man:	Supervisor:		PT:		
	Date:	Date:		Date:		

NO.	WORK ELEMENT	Icon	KEY POINT Safety, Quality, Technique, Cost	Time Elements Auto	Manual	Wait	Walk
1	Set up						
2	Autotest						
3	Unload the gauge						
4	check result and print the data						
5	Collect data from printer						