Applicability of Lean Manufacturing and Quick Response Manufacturing in a High-Mix Low-Volume Environment

by

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Submitted to the Sloan School of Management
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Abstract

As today's manufacturers face increasing pressure to improve costs and compete globally, many are turning to the philosophy of Lean Manufacturing as exemplified by the Toyota Production System. Lean is most successful when production is characterized by a few high-volume products, but may not be the answer as the production mix increases and volume decreases.

This thesis focuses on this high-mix, low-volume type of production in addition to two other key production system characteristics: demand variability and degree of customization. A manufacturer's position along these four characteristics is very important to the applicability of Lean theory. The alternative philosophy of Quick Response Manufacturing (QRM) is compared to Lean and shown to offer a better fit in some cases. One such case where Lean does not fit neatly is circuit card assembly at Raytheon Systems Limited in Glenrothes, Scotland, where the author conducted his six-month LFM internship.

Five steps towards manufacturing improvement are focused on in this thesis: choosing metrics, reorganizing the factory, selecting lot sizes, implementing a production control strategy, and deciding on a material presentation method. The recommended steps to improve circuit card assembly include ideas from both Lean and QRM.

This mix of ideas was implemented at Raytheon before the end of the internship and resulted in marked improvement. On-time delivery and customer satisfaction dramatically improved while lead times and inventories dropped significantly. Using Lean Manufacturing as the sole guideline for improvement was not appropriate for this particular manufacturing system. The final takeaway from the internship and thesis is that there is no one-size-fits-all manufacturing philosophy.

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Next I thank some of my fellow LFM students who helped me during my internship – Michelle Berson, Satish Krishnan, and Matt Gates.

I also must thank the contributors to an internet discussion group, who gave me a great deal of food for thought. The “Job Shop Lean” group on Yahoo! introduced me to Quick Response Manufacturing and really got me thinking about how much Lean really applies to a high-mix, low-volume environment.

Lastly I thank all the great people at Raytheon in the UK who were a part of my project. The internship was well defined from the start, thanks to my project sponsor, Alastair Blair, and my project supervisor, Gordon Scotland. Gordon was a true partner in my project and many of the ideas in this thesis are a result of the many long discussions I had with Gordon over the course of the internship. I also want to thank him for giving me the opportunity of a real leadership experience.

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CMI Disclaimer

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1. Introduction

As today's manufacturers face increasing pressure to improve costs and compete in a global marketplace, many are turning to the philosophy of Lean Manufacturing as exemplified by the Toyota Production System. TPS has been shown to simultaneously reduce costs, improve quality and reduce product cycle times in many manufacturing environments. TPS is most successful when production is characterized by a few high-volume products, such as an automobile assembly line. However, as the production mix increases and product volume decreases, TPS may not be the answer.

This thesis focuses on this high-mix, low-volume type of production in addition to two other key production system characteristics: demand variability and degree of customization. A manufacturer's position along these four characteristics is very important to the applicability of Lean Theory. The alternative philosophy of Quick Response Manufacturing (QRM) is compared to Lean and shown to offer a better fit in some cases.

1.1. Thesis Structure

The thesis is organized into four main sections. The first section contains Chapters 1 and 2 and provides some background. Chapter 1 defines the four key production system characteristics and introduces the idea that all manufacturers fall somewhere along a continuum for each of these characteristics. This chapter also provides background on the LFM internship project at Raytheon Systems Limited in Glenrothes, Scotland. Chapter 2 contains a literature review of Lean Manufacturing, Quick Response Manufacturing, and various production control methods.

The second section explores the application of Lean and QRM as methods to improve manufacturing performance. Five steps towards improvement are focused on: choosing metrics, reorganizing the factory, selecting lot sizes, implementing a production control method, and deciding on a material presentation method.[1] For each of these steps, the appropriate ideas from Lean and QRM are described. In addition, the application of these ideas in Glenrothes is addressed. Glenrothes is a case study for the type of production environment where neither Lean nor QRM is a perfect fit. A careful analysis of the application of Lean principles and QRM principles in this environment shows that Lean works best is some cases and QRM in others. It is also shown that these two philosophies are not always mutually exclusive and can sometimes overlap or co-exist in some form to produce the best production system.

The third section of the thesis contains an analysis of the organizational change process during the internship. This is explored using three perspectives or lenses: strategic design, political, and cultural. The final section of the thesis first captures the accomplishments over the course of the internship. It also includes a summary of the analysis of Lean and QRM and their application in Glenrothes. Lastly, some final recommendations for Raytheon Glenrothes are presented.

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[1] This is not a complete list of all possible improvement steps. The first four are critical to any manufacturing system improvement effort, while this fifth is included due to significant study during the internship.

1.2. Four Key Production System Characteristics

1.2.1. Mix

Mix refers to the number of different products that are produced within a certain production system. What makes one product "different" from another? One answer is the end product differences, such as number of parts, functionality, appearance, etc. This definition is not very useful, however, for the purposes of understanding mix within the production system.

A more appropriate method of understanding product differences here is to compare the different processes or steps that products must take as they move through production and the difference in processing time at each step. Two products may look different to the customer, but if they are produced with identical routings through the plant, require no setups from one product to the next, and require identical processing times, then these products are not really "different" and do not contribute to higher mix. However, two other products that appear to be similar might travel completely different routes through the factory, and even the processes they do share have unique setups and very different process times. These types of products contribute significantly to the factory mix.

1.2.2. Volume

Volume is the quantity of a product produced over a specific period of time. Knowing whether a product is high volume or low volume is difficult to define because it depends so greatly on one's perspective. To a company such as Intel that produces millions of semiconductor chips a year, a product with a 100-unit-per-month volume would be considered low volume. To the employees of a space satellite manufacturer, this type of volume would seem very high. They can usually count the number of products produced per month on one hand.

The most important aspect of product volume for this thesis is whether on not the product can be produced continuously in manufacturing without overproducing. For example, Intel's microprocessors obviously fall into the high-volume category since the same product is run through the identical process routings day after day. Automobiles at Toyota also fall into this category. Even though 3-4 models are produced on one assembly line, the sequence is run continuously throughout the day. Any product that falls outside this is then by default low-volume.

Even this definition is not perfect because some products that might be produced continuously are run in batches by companies trying to reduce setup time and costs. The question that should be asked is: can this product be run on a dedicated line by itself or alongside other similar products without any significant changeovers? If the answer to this question is no, then it meets the requirement for low-volume.

1.2.3. Demand Variability

Demand variability is defined as the changes in customer demand over time. How different are the customers' orders between order cycles? The time between cycles could be fairly long (weeks or months) in slower-moving industries such as aerospace and defense or very short (hours in the case of Dell). The more the demand for specific products fluctuates from order to order, the higher the demand variability.

It is important to note that total demand could be relatively constant, but demand by product varies between order periods. If the demand differences occur on similar products with similar routings and processing times in the factory, then the contribution to demand variability is minimal. If these different products have very different routings and processing times, then the change in the "mix" of demand, even with the total demand remaining constant, will contribute to higher demand variability as defined in this thesis.

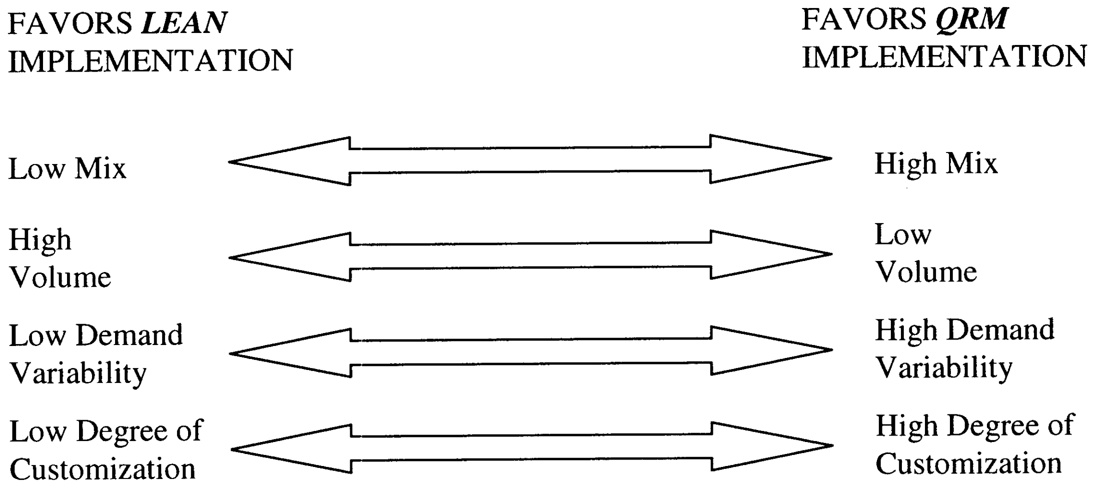
1.2.4. Degree of Customization

Manufactured products can be standardized on one end of the spectrum or customized on the other end. Standard content includes materials and parts that repeat between orders of a given product. Customized content refers to materials and parts that are unique to a particular order. The most extreme example of a customized product is one that is designed and produced only once. The international space station is such a product: although some components might have other uses, this is a one-of-a-kind product that is highly customized. On the extreme "standard" end of the spectrum are highly commoditized products such as basic fasteners and electrical devices (capacitors, resistors). These products do not change from order to order. They remain unchanged over long periods of time and can be manufactured in a repetitive manner.

1.2.5. Key System Characteristics Continuum

The characteristics of mix, volume, demand variability, and degree of customization can be identified for a specific manufacturer and plotted on a continuum as shown in Figure 1.

Figure 1: Key Production System Characteristics Continuum



It is very important to understand where a particular manufacturing system is located along this continuum for each of the key system characteristics when initiating improvements. Lean Manufacturing fits very well in environments that fall to the left on each of the four system characteristics. However, as the manufacturing system is characterized by increasingly higher mix, lower volume, higher demand variability, and higher customization, the appropriateness of

Lean Manufacturing diminishes.[2] Another philosophy, Quick Response Manufacturing, is designed for systems whose key characteristics fall to the right on the Continuum.

1.3. Thesis Hypothesis

With the Key System Characteristics Continuum defined, the central hypothesis of this thesis can be stated in three parts:

1. Lean Manufacturing is applicable to low mix, high volume, low demand variability, low degree of customization environments, but is not necessarily applicable to all production environments.
2. Quick Response Manufacturing offers ideas that are more applicable than Lean to an environment that is characterized by high mix, low volume, high demand variability, and high degree of customization.
3. A mix of Lean and QRM philosophy is best in production environments that do not fall on the extreme ends of the Continuum.

1.4. Case Study at Raytheon Systems Limited

The applicability of Lean and QRM will be explored in an environment that does not fit neatly on either end of the Key Production System Characteristics Continuum: circuit card assembly at Raytheon Systems Limited in Glenrothes, Scotland. The author conducted his six-month Leaders For Manufacturing internship at this site. A number of changes were made to the manufacturing system at Raytheon based on the application of Lean and QRM improvement techniques.

1.4.1. Raytheon Glenrothes

The Glenrothes manufacturing plant is part of Raytheon Systems Limited, a company that encompasses all of Raytheon's facilities in the United Kingdom. The plant manufactures electronic systems for high-reliability applications for the government and industrial sectors.

1.4.2. Circuit Card Assembly

The internship was centered on the circuit card assembly (CCA) portion of the operations. This is also referred to in the industry as PCB (printed circuit board) assembly. The terms "board" and "card" will both be used to refer to a circuit card. The Glenrothes plant purchases the base PCB board along with thousands of components from other electronics manufacturers. The components are then assembled at the plant using a combination of automated and manual assembly techniques to create a completed circuit card. This card is then tested electronically for functionality and visually inspected before being shipped to the customer.

The technology used to assemble circuit cards has changed significantly over the past 20 years from mostly manual assembly to nearly 100% automated assembly, and from inserting components through the board (through-hole) to placing components on top of the board (surface-mount). Raytheon Glenrothes assembles boards with a mix of these technologies because most of its circuit cards have a long product life cycle. Some cards produced at

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[2] This statement will be seen as controversial by many in the manufacturing community, where Lean is often seen as the appropriate philosophy for all types of manufacturing. The experience of the author while on this internship is evidence that Lean is less applicable in certain environments.

Glenrothes are still predominantly through-hole requiring almost 100% manual assembly. The main types of assembly equipment used at Glenrothes include SMT (Surface Mount Technology), automated through-hole, and semi-automated through-hole. All surface mount components that are not placed by manual assembly are placed by SMT machines. This is the most productive method for assembling circuit cards.

Those through-hole components that are not inserted and soldered manually are fixed to the board using either an automated or semi-automated process. The automated through-hole process is about 30% as productive as SMT. Semi-automated through-hole equipment, which is sometimes needed because of it's capability to place a wider range of components than the auto-through-hole machine, is only 10% as productive as SMT. The manual assembly of components, which is predominantly through-hole, ranges widely in productivity but is always the least productive method for assembling circuit cards. Not all circuit cards pass through each one of these assembly stages, but a majority of them require at least two of these processes.

1.4.3. Key Production System Characteristics of Circuit Card Assembly

Glenrothes produces over 200 different types of circuit cards. This production is categorized as high-mix using the definition given in 1.2.1 because most of these cards travel different routes through the factory and processing times range from minutes on some cards to hours on others. Figure 2 shows the routings for a sample of 30 circuit cards.

Figure 2: Process Routings for 30 Sample Circuit Cards

	Process Number																					
Product No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Product 1	x			x	x		x	x	x				x				x			x	x	x
Product 2	x			x	x		x	x	x				x				x			x	x	x
Product 3	x				x		x	x	x				x				x	x	x		x	x
Product 4	x						x	x	x				x				x	x	x		x	x
Product 5	x						x	x	x				x				x	x	x		x	x
Product 6	x					x	x	x	x			x	x				x				x	x
Product 7	x	x	x			x		x	x				x				x				x	x
Product 8	x	x	x			x		x	x				x				x				x	x
Product 9	x			x			x	x	x				x				x			x	x	x
Product 10	x			x			x	x	x				x				x			x	x	x
Product 11	x	x	x									x					x				x	x
Product 12	x	x						x	x			x	x				x			x	x	x
Product 13	x	x	x		x			x	x				x				x				x	x
Product 14	x	x	x									x	x				x				x	x
Product 15	x	x	x									x					x				x	x
Product 16	x	x											x				x				x	x
Product 17	x	x											x		x	x	x				x	x
Product 18	x	x											x		x	x	x				x	x
Product 19	x	x											x		x	x	x		x	x	x	x
Product 20	x	x											x		x	x	x				x	x
Product 21	x	x	x									x	x		x		x				x	x
Product 22								x				x		x	x		x		x		x	x
Product 23										x	x		x	x	x		x		x		x	x
Product 24								x	x				x								x	x
Product 25								x	x				x								x	x
Product 26	x	x		x																	x	x
Product 27	x	x		x																	x	x
Product 28	x												x		x		x		x		x	x
Product 29													x	x	x		x		x		x	x
Product 30	x									x	x		x	x	x						x	x

For example, Product 17 must travel through Processes 1, 2, 13, 15, 16, 17, 21, and 22 before it can be delivered to the customer. Some of these process steps are performed within one work center, but most are discreet processes. Also, circuit cards may repeat some steps if there are quality problems.

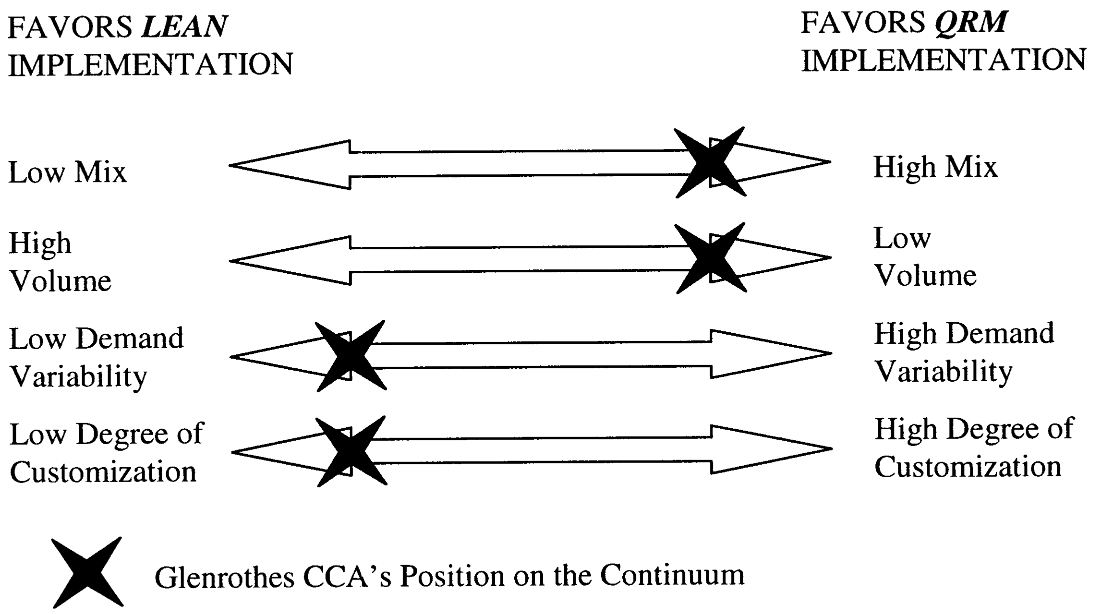
Volume per month at Glenrothes ranges from 2 to 200 cards per card type. This falls into the definition of "low volume" because there is not enough volume to support a dedicated line for any of these products. To further support the low volume categorization, the CCA industry identifies low volume as less than 30,000 circuit cards per year.

Most circuit cards are supplied to customers that build electronic systems on a long term contract. These systems typically have a regular build schedule each month that is known weeks ahead of time. This means most circuit cards have a fairly stable demand and any demand changes will be known weeks in advance. There are exceptions to this. If a group of circuit cards fails at a customer, a new order for that card might come earlier than expected. However, this does not happen very frequently. Therefore circuit cards in Glenrothes are best characterized by low demand variability.

Circuit cards at Glenrothes have a low degree of customization from order to order. Engineering changes do come through from time to time, but these can be planned for and managed on an exception basis. The vast majority of card types are built the same way every time.

These production characteristics for circuit card assembly can be plotted on the Key System Characteristics Continuum as shown in Figure 3.

Figure 3: Key System Characteristics for Glenrothes



Two of the characteristics fit a Lean implementation (demand variability and degree of customization), while two others fit a QRM implementation (high mix and low volume). The right philosophy to improve manufacturing performance is not clear in this case. This gives us an excellent chance to explore how Lean and QRM concepts compare in a "mixed system characteristics" environment.

1.4.4. Circuit Card Production History

Circuit cards have been produced at the Glenrothes site for over a decade. Prior to the beginning of the LFM internship, two Raytheon UK circuit card assembly sites were consolidated into the Glenrothes facility. This more than doubled the variety and volume of existing cards. Equipment from the other facility (referred to as Plant B or Customer B) was transferred to Glenrothes and production began six-months before the internship start date. Most of the cards transferred to Glenrothes were shipped to Plant B after assembly for inclusion in higher-level electronic systems. Thus Plant B became Glenrothes' largest customer of circuit cards.

The state of circuit card production at the beginning of the internship was not good by any measure. Plant B was already behind in orders before production was transferred, and a substantial increase in orders accompanied the transition. Quality was achieved through significant rework, a condition that remained unchanged after the transfer. The computerized planning (MRP) system was launching circuit cards into production to meet this backlog, clogging the floor with inventory. Significant time was being spent by production personnel, engineering, and management to expedite "hot" cards through the system. It was taking upwards of 12 weeks for a card to ship to the customer once it had started the assembly process. Finally, deliveries were late on nearly 40% of the circuit cards needed by Customer B.

An improvement team was created to tackle these problems. This team consisted of representatives from numerous functions, including engineering, quality, operations, and supply chain. The author joined this team at the beginning of the internship. At this point, the team was in the midst of implementing Lean Manufacturing within circuit card assembly.

2. Literature Review

2.1. Lean Manufacturing

Lean Manufacturing is a term coined by James Womack, Dan Jones, and Daniel Roos in their book "The Machine that Changed the World", a study of the post-WWII auto industry. Womack and Jones showed that there was a marked difference between quality and productivity levels among American, European, and Japanese automakers, with the Japanese holding a clear advantage. This advantage can be traced to the manufacturing philosophy of the Japanese companies, with Toyota the prime example of how Japanese auto manufacturing differed from US or European producers.[3] The Toyota Production System ("TPS"), as it is now known, is the basis for Lean Manufacturing principles. A follow-up work by Womack and Jones, "Lean Thinking", generalizes Lean principles beyond auto manufacturing.

At its heart, Lean Manufacturing is the relentless pursuit of the elimination of "muda", or waste, in all parts of production. Waste is defined as any activity that does not provide value in the eyes of the customer. The seven wastes as defined by Taiichi Ohno, the founder of TPS, include overproduction ahead of demand, waiting for the next processing step, unnecessary transport of materials, overprocessing of parts due to poor tool and product design, inventories more than the absolute minimum, unnecessary movement by employees during the course of their work, and production of defective parts.[4]

There are five steps in the journey towards Lean Manufacturing. The first is to define *value* from the customers' perspective. Most manufacturers include process steps that they feel are needed but are not valuable to the customer, such as quality checks or transferring inventory between steps. Although these steps may be needed in the current production system, they do not add value in the eyes of the customer.[5]

The second step is to identify the *value stream*, which is the set of actions required to manufacture and deliver a specific product. Ideally the value stream can be identified from the most basic raw materials all the way to the end customer that uses the product. This value stream "mapping" will uncover obvious wasteful activity that is clearly non-value added and can be eliminated immediately.[6]

The next step in a transformation to Lean is to make the remaining, value-creating steps *flow*. Traditional manufacturing breaks work down to specialized steps that are very "efficient" when viewed in isolation. Products travel from department to department, waiting in front of specialized machines before being processed in large batches. Lean thinking rejects this traditional manufacturing mindset in favor of the idea that material should flow smoothly between value-creating steps. Products should not be made in batches, but instead should move

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[3] James P. Womack, Daniel T. Jones, and Daniel Roos, The Machine That Changed the World, (New York: Harper Perennial, 1990)

[4] James P. Womack and Daniel T. Jones, Lean Thinking, (New York: Simon & Schuster, 1996), 309-310

[5] Ibid., 16-19

[6] Ibid., 19-21

in single units through the factory waiting as little as possible and moving the least distance possible.[7]

The fourth step in a Lean transformation is to let the customer *pull* the product as needed rather than push products onto customers. In a perfect Lean value chain, no operation is started until the upstream operation indicates it is needed.[8]

The last step is not one that can actually be implemented, but a goal to strive for: *perfection.* Perfection is achieved when all waste from a process has been eliminated and product flows effortlessly at the pull of the customer. This drive for perfection is what keeps companies like Toyota, who are far ahead of most of the competitors in terms of quality, cost, and profit margin, from becoming complacent. There is always more waste to uncover and never an end to continuous improvement.[9]

Becoming "lean" is a major objective for many corporations, including Raytheon, the sponsoring company for the internship. Lean has been written about for nearly 15 years, but it still holds a strong appeal, particularly within LFM partner companies. Some form of Lean Manufacturing implementation was the subject of ten internships this year.

Lean is also at a point where its definition is becoming diluted. For many people, it has become synonymous with anything good for manufacturing – if you are improving manufacturing, it must be getting leaner. It also is purported to be universally applicable. The authors of Lean Thinking do not suggest limiting the application of Lean to any particular type of manufacturing system. To Womack and Jones, all products and even services would be improved by applying the five Lean steps. This has given rise to a mantra by many companies that they must get "lean" in all products and processes. The executives at these companies may not be quite sure what that actually means, but they do believe their business will be better off for it.

2.2. Quick Response Manufacturing

Quick Response Manufacturing is a manufacturing philosophy exhorted by Professor Rajan Suri at the University of Wisconsin. He authored the book "Quick Response Manufacturing: A Companywide Approach to Reducing Lead Times" in 1998 that explains what QRM is, where it is applicable, and how to implement it in manufacturing. In a nutshell, QRM is the pursuit of ever decreasing lead times, [10] with lead time defined as the time it takes from customer order to fulfillment of that order.[11]

Suri suggests that this singular focus on lead time is the right strategy for certain companies or certain markets. These companies are characterized by a high variety of different products that are produced in one manufacturing system, customers who demand highly customized products,

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[7] Ibid., 21-24

[8] Ibid., 24-25

[9] Ibid., 25-26

[10] Rajan Suri, Quick Response Manufacturing, (Portland, OR: Productivity Press, 1998), 4

[11] The terms lead time and cycle time are taken to mean the same thing for the purposes of this thesis. The lead time or cycle time of a portion of the manufacturing process is defined as the average time it takes for a product to complete this portion of the process.

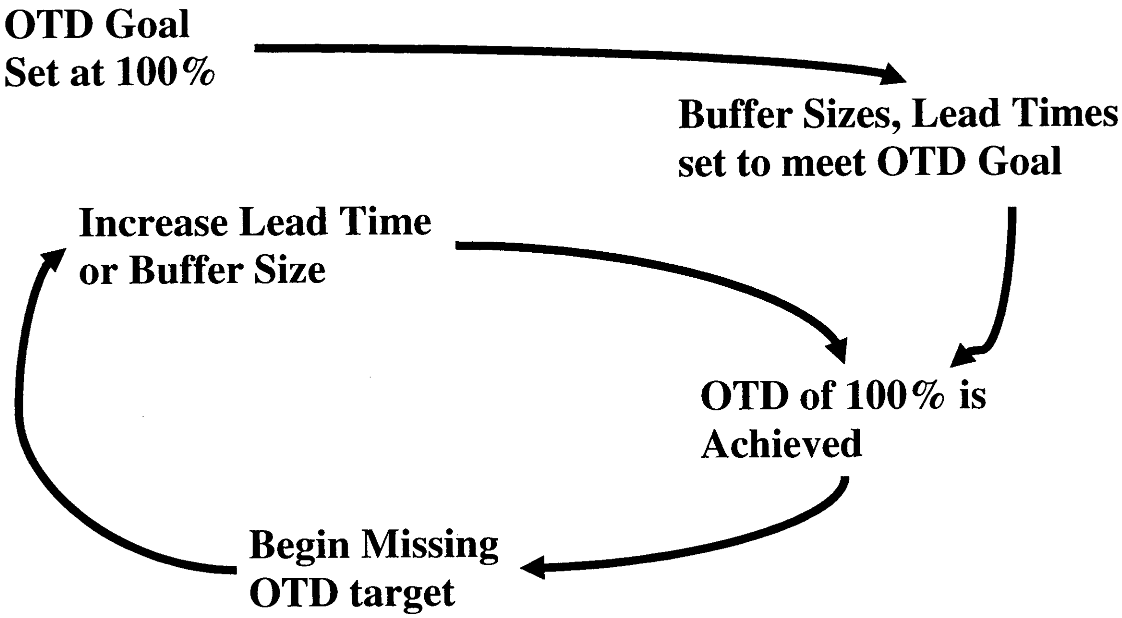
and where demand is highly variable.[12] The largest benefit with QRM is seen when the customers for these products value short lead times from a supplier over long lead times. Quick Response Manufacturing is a way to drive down lead times to both create a competitive advantage in the marketplace and improve the internal manufacturing operations.

QRM starts with ten basic principles that debunk some widely held beliefs in most manufacturing companies.[13] Here a few examples:

- Do not attempt to operate with people and machines at full capacity: Operate at 70% to 80% capacity on critical resources to accommodate system variability.
- Do not focus on individual machine efficiencies to reduce lead time; instead, measure the reduction of lead times and make this the main performance measure.
- Do not place great emphasis on "on-time delivery" measures. Over time, this will work against lead time reduction. Instead, measure lead time – improvements in this metric will lead to improved on-time delivery performance.
- Scrap quantity discounts from suppliers and to customers and move towards smaller lot sizes.[14]

QRM uses system dynamics to help analyze a manufacturing system. The most important concept to understand using this approach is the "Response Time Spiral" shown in Figure 4.

Figure 4: Response Time Spiral



Most companies rely heavily on on-time delivery as a primary metric for factory performance. They also usually place emphasis on efficient machines/work centers that are highly utilized.

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[12] Rajan Suri, "Quick Response Manufacturing: A Competitive Strategy for the 21st Century" (Proceedings of the 2002 POLCA Implementation Workshop, 2002), xiv

[13] Suri, 1998, 18-22

[14] The complete list of QRM principles are given in Suri's 1998 text on pages 18-22.

Machines running at near capacity tend to create significant queues in front of them, which drives up lead times. Over time companies find themselves missing deliveries because the desire to operate the system near peak capacity works against the on-time delivery goal. A factory manager's response to slipping on-time delivery metrics is usually to ask his/her management for longer promised lead times to customers. Senior management often goes along with this reasonable request because the factory seems to be running very "efficiently" (i.e., each work center is highly utilized). In order to avoid serious customer service issues, the promised lead time is lengthened or the product is excessively buffered. As this cycle repeats over time, lead times continue to grow.[15]

Certain steps are needed to implement QRM. After making lead time the driving metric, production must be reorganized away from functional centers and into product-focused cells.[16] The next step is to change to lot sizes that minimize lead time.[17] Then a new production control system can be implemented, with the MRP system being used for material planning and a unique system called "POLCA" used to manage the flow of products through the factory.[18]

QRM is much less well known and widely used than Lean Manufacturing. This is understandable for two reasons; Lean has been around longer, but more importantly, Lean is seen as universally applicable to all manufacturing systems. QRM does not purport to fit all manufacturing systems, but those that are high mix, low volume, with highly variable demand and highly customized orders.

2.3. Production Control Methods

2.3.1. Push vs. Pull

The five different methods for controlling the movement of product from the beginning to the end of production described in this section of the thesis can all be characterized as either a push or pull system (or some combination of the two.) In a basic push system, product that completes one process step is pushed to the next step. Production does not stop as long as there is product awaiting that process step. Inventory is allowed to build up in front of less productive machines in this type of system.

In contrast to a push-style of production control is pull. In a basic pull system, production does not commence at a specific processing step until the downstream process sends a signal, usually in the form a certain level of inventory between the processes. Product might be waiting in front of that processing step, but production cannot commence until the downstream process "demands" it.

2.3.2. MRP

Material Requirements Planning (MRP) is a computerized system that is typically laid on top of a traditional "push" manufacturing system with a functional layout. A functional layout is one where like machines are grouped together in "work centers" or "departments." Products usually

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[15] Suri, 1998, 53-67

[16] Ibid., 89-91

[17] Ibid., 165-173

[18] Ibid., 246-247

need to pass through many of these work centers, and managing what product goes to what work center when becomes a daunting task as the number of work centers and products increase.

Many companies have implemented an MRP system to handle this complexity. An MRP system can be programmed with the routings of all products and a reasonable time for each product to pass from one work center to the next. By combining these routings and processing times, a promised lead time can be generated for every product that starts on the factory floor.

MRP systems can run into problems because of the variability that is present in every manufacturing system. Any hiccup in production, such as a machine going down or a process taking quite a bit longer than expected, starts a ripple in the system that usually magnifies. The product that gets behind will now reach the next work center at a different time than originally planned. This work center might now be working on the next product that MRP has planned, so either this must be broken into or the other product must be delayed further. As the variability effects add up, products get behind schedule and need to be expedited through the system.

There are improved MRP systems that deal with variability more effectively. But rather than try to put a band-aid on a poor production control system, many companies use simpler, less computerized production control systems that work more effectively.

2.3.3. Kanban

The first of these lower-tech alternatives is Kanban, the production control method used for Lean Manufacturing and the most widely used form of "pull". In order for Kanban to be implemented, production must be organized in such a way that a product or group of products follows the same sequence through the factory on dedicated equipment.

Kanban works by limiting the inventory between each step in a production process. Cards are created for each process step. Work cannot begin at a particular step until that step receives a card from the upstream process. Work therefore does not build up between work centers because the number of cards is limited. Kanban is the ultimate form of "pull" production because every step waits from the downstream step to signal or pull material rather than just produce what is placed in front of the process.

Kanban creates a very tight production system that is intolerant of variability. The failure of one step in the chain will quickly ripple through the system and shut down the other processes in the chain. An initial Kanban implementation will often result in poorer production performance because of this. But Lean proponents insist this is only way to expose the problems in the process and eliminate the variability instead of living with it.

2.3.4. CONWIP

One alternative to Kanban is CONWIP, a production control strategy devised by Spearman, Woodruff, and Hopp.[19] CONWIP stands for Constant Work In Process, and it operates by fixing the amount of inventory that can be on the factory floor at any one time. This limiting of

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[19] Mark L. Spearman, David L. Woodruff, and Wallace J. Hopp, "CONWIP: A Pull Alternative to Kanban," (Article Published in 2001)

inventory indicates it is form of pull production control. Usually this works by requiring that a unit can only be issued to the line once another unit has completed production.[20]

The guiding principle behind CONWIP is Little's Law:

$$\text{Average Lead Time} = \frac{\text{Average Inventory}}{\text{Average Throughput}}$$

This implies that with inventory fixed, lead time will change linearly with throughput. If demand is fairly constant over time (and a similar throughput is needed over time), then the easiest way to manage lead times is to fix inventory levels. The same principle is at work behind Kanban, but CONWIP allows more flexibility.

First, CONWIP does not specify where the inventory must collect in a system. Kanban puts a cap on inventory between each process step, while CONWIP just places an overall cap. This allows the inventory to collect before the constraint in the system and actually leads to a higher throughput than in a Kanban system. With Kanban, the constraint is starved more often than in a CONWIP system. CONWIP also is more flexible in that it does not require a dedicated process with linear flow. CONWIP could even be applied in a traditional functional environment.[21]

2.3.5. POLCA

The production control system favored by QRM is called POLCA (Paired-cell Overlapping Loops of Cards with Authorization), another form of pull. This system combines elements of Kanban, CONWIP, and MRP to create what Dr. Suri believes is the best system for QRM-suited environments. A thorough explanation of POLCA would be very lengthy and not appropriate for a literature review summary. A complete explanation can be found in Suri's 1998 book.[22]

With POLCA, Cards similar to Kanban are created for pairs of cells (or pairs of work centers). This allows for flexibility in the system so that products can take different paths through the factory (unlike Kanban). The number of cards is finite, capping the inventory in the system as in CONWIP. In order for production to begin at a particular process step, a card must be available and the work must be authorized by the MRP system. This authorization step is included to make sure a product that is well ahead of schedule does not tie up a process for a long time. Work that is on schedule or behind will not be blocked by the product that is ahead of schedule.

POLCA can work with a functional layout, but is made much less complicated by the implementation of some groups of machines or processes into cells. POLCA is the system used between these cells. Suri does not specify the production control system to be used within the cells, so the complete production control system could be a combination of push and pull or just two different forms of pull.[23]

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[20] Ibid.

[21] Ibid.

[22] Suri, 1998, 243-255

[23] Suri suggests using whatever production control method the cell team decides is best for their cell. This could be some form of push, CONWIP, Kanban, or Drum-Buffer-Rope.

2.3.6. Drum-Buffer-Rope

A fourth production control method is called "Drum-Buffer-Rope" or DBR. DBR uses a combination of pull and push. This method is described in Eli Goldratt's book on the Theory of Constraints.[24] The first key element of this system is the "drum", or main constraint. This is the process step that has the least amount of excess capacity and controls the total throughput of the plant. The drum is scheduled to produce maximum output. In order to keep the drum from running out of parts to process, a buffer of inventory is maintained before the drum. The "rope" is a signal from the drum back to the beginning of the process that triggers the release of material.

Downstream of the drum, product is pushed through to the end of production. This is not of great concern under the Theory of Constraints because the downstream processes should have plenty of excess capacity. Product should therefore flow rather quickly downstream of the drum even in push mode.

The part of the process between the drum and the rope is very similar to CONWIP production control. Setting a buffer level and linking the drum to the beginning of the process is just how CONWIP works. The main difference with Drum-Buffer-Rope is that the pace-setter is in the middle of the process and not the last production step.

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[24] Eliyahu M. Goldratt and Jeff Cox, The Goal, (Gower Publishing Limited, 1986)

3. Manufacturing Metrics

3.1. Cost, Quality, Delivery, Flexibility

Cost, quality, delivery, and flexibility are four of the most important attributes for determining the performance of a manufacturing system. Manufacturers would like to make the highest quality product at the lowest cost and deliver it exactly when the customer wants it. They also desire the flexibility to be able to change quickly with industry trends or changing customer demands.

For most of the 20th century, manufacturers believed each one of these attributes had tradeoffs. To achieve better quality, costs would have to rise. Costs could be reduced by automating processes, but this reduces flexibility. Delivery can be guaranteed with piles of finished goods inventory, but this inventory is an added cost for the company.

3.2. Waste vs. Lead Time

Significant changes to this "trade-off" idea occurred in the latter half of the twentieth century. Proponents of Lean Manufacturing claim that implementing Lean simultaneously improves quality, reduces cost, improves on-time delivery, and increases flexibility. This could be accomplished by the constant drive to eliminate waste from manufacturing. Toyota is a very good example of the positive effects of a Lean Manufacturing system on these four attributes. Toyota manufactures lower-cost, higher-quality cars than non-Lean auto manufacturers.[25] They also have the flexibility to produce multiple models on one assembly line.

Quick Response Manufacturing focuses on a different driving metric to improve manufacturing: lead time. Proponents of this philosophy believe that by reducing the time it takes to produce a product from order to delivery, total costs go down, and quality, delivery, and flexibility all improve. Products with very short lead times are simpler to manage, therefore overhead costs are low.

These two driving metrics of waste and lead time are not mutually exclusive. Lean systems usually result in much shorter lead times than the systems they replace. Systems that have implemented QRM contain much less waste than a non-QRM system. So why be so concerned about the particular metric one chooses to drive manufacturing improvement if they both produce the desired results? This will be explored in the context of CCA production in Glenrothes.

Another pertinent question is "Why does there have to be a focus on a single metric?" Why not use all four attributes of cost, quality, delivery, and flexibility as the basis for improvement? This is an option, but there are two reasons why a single metric is preferable over this approach. First, using four metrics can lead to an improvement in one metric over the detriment of the others. This is the "tradeoff" problem already mentioned. For example, a manager could see an opportunity to save on labor by reducing inspection costs, but quality may be negatively affected by this move. Second, a single metric creates a rallying point for everyone in manufacturing.

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[25] James P. Womack, Daniel T. Jones, and Daniel Roos, The Machine That Changed the World, (New York: Harper Perennial, 1990)

This leads to a focused workforce that is always looking for ways to eliminate waste (Lean) or drive down lead time (QRM).

If a manufacturer has identified its own production as being on the "Lean" end of the four characteristics of mix, volume, demand variability, and degree of customization, then a sole focus on waste is a very appropriate method to drive improvement. If, on the other hand, the manufacturing system has identified with being on the QRM end of the spectrum, then lead time is a more appropriate driving metric. What about manufacturers that fall somewhere in between, such as Raytheon Glenrothes? This is a much more difficult question, but can be explored using the internship as a case study to illustrate the effects of a focus on waste vs. a focus on lead time.

3.3. Waste vs. Lead Time at Glenrothes

Raytheon Glenrothes is characterized by high mix, low volume, stable demand, and standard products as explained in 1.4.3. The first two characteristics call for QRM methods, while the latter two fit a Lean production system.

At the beginning of the internship, the improvement team was operating under the "Lean Manufacturing" banner. It was assumed that Lean was the best production system for all environments, and that "Leaning" out circuit card manufacturing would lead to improvement.

Following the Lean methodology, the team began to identify the various wastes in the system. In a typical Lean implementation, a value stream map is created as a guide to identifying which parts of the process are value-adding and which are waste. This map shows all the production steps and information flows needed to complete a product. Raytheon's method for implementing Lean deviated somewhat from strict Lean principles here because a formal value stream map was not created. Waste was identified in a less formal manner, and the subsequent steps of the Lean implementation process, creating flow and pull, were emphasized.

Certain waste was identified by the Lean implementation team through brainstorming sessions without the help of the value stream map. The wastes that were focused on can be put into the following priority list:[26]

1. Unnecessary movement of employees
2. Overproduction ahead of demand
3. Unnecessary transport of materials
4. Production of defective parts
5. Excess inventories

The wastes of waiting for the next step and overprocessing because of poor tool/product design were not addressed with the initial Lean efforts.

Unnecessary Movement of Employees

This was seen by management as the largest source of waste in production. They often observed operators talking to each other about non-work related topics outside of break times and wasting time by looking for parts or production instructions. Direct labor was a very important factor in

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[26] This list has been created ex-post. This priority was not formally used during implementation, but does represent the relevant importance of the various types of waste to the team.

the calculation of total product cost, so any time wasted by the operators hit the bottom-line directly.

This waste was addressed by a number of initiatives. The first of these was the creation of accurate, easily accessible production instructions in the manual assembly portion of the process. This is commonly referred to as "standard work" in the Lean lexicon. The second was a change to the way material was presented to the line to reduce the need to "hunt" for parts. This is explored in detail in Chapter 7. Other proposals involved some form of better supervision to prevent the personal conversations between operators, but no significant action was taken on this front.

Overproduction Ahead of Demand

The main tool to address overproduction ahead of demand was to implement a pull system, which is described in detail in Chapter 6. As part of the initiative to reduce overproduction, all product that was on the production floor that was deemed not needed in the next month was pulled back to an upstream "buffer" of inventory.

Unnecessary Transport of Materials

This was addressed in two ways. The first was the layout of the production floor. Machine and assembly workstations were all located in the same footprint on the production floor so that product never had to leave that part of the building from start to finish.[27] This was effective in minimizing travel distances. The second was the implementation of point of use materials. (Explored in Chapter 7)

Production of Defective Parts

There was a significant amount of rework generated by CCA production. A couple of changes were made to improve this situation. First, all rework was moved to a central location so the amount and severity of rework could be observed. Prior to this all rework was performed at employee work benches, which hid the magnitude of the problem. Second, standard work for the manual assembly steps was created to better instruct operators on the right way to assemble a board.

Excess Inventories

This was not a high priority for the Lean implementation team. An attempt was made to institute a rule to limit inventory in front of certain work centers to less than a day's worth, but inventory still was allowed to pile up in front of most work centers. Excess inventory was addressed to some degree with the implementation of a modified pull system that is described in detail in Chapter 6.

The actions to remove waste at the beginning of the project did have some impact on circuit card assembly performance. The removal of excess circuit card work-in-process inventory temporarily dropped lead times. However, none of the initial steps to reduce waste resulted in major improvements in delivery, cost, or quality. The author argues that this is due to the

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[27] Some products did require a bonding step that was in a small building 100 feet from the production floor. The chemicals used in this process had to be kept a distance from normal production to avoid contamination.

piecemeal nature of the actions to eliminate waste. Attacking a little waste here and a little waste there is not going to have dramatic effects on overall system performance. Lean proponents would argue that the initial identification of obvious non-value added activity does not always generate the biggest gains. These gains should come by implementing flow and pull. Chapters 4 through 6 of this thesis explain how well these next steps in a Lean transformation can be implemented in an environment that is not a perfect fit for Lean.

Another drawback to a sole focus on waste elimination is the potential harm to the system by removal of buffers. Buffers of inventory and capacity are very important in a system characterized by high mix and variability in demand. These buffers help manage the variability in production requirements from time period to time period. Removing inventory and capacity buffers can seriously hurt production performance.[28] It would be preferable to smooth out the variability in mix and demand so that less buffering is needed, but this is not always possible. Taking out the "waste" of inventory and excess capacity before understanding the system variability can lead to disastrous results.

One final drawback to using waste as the driving metric: it is very difficult to measure progress against this metric. Waste comes in many forms, so one cannot easily devise a number that represents current total waste and the target waste level. This can be done indirectly by attaching costs to specific forms of waste, but this creates a bias where only waste that has direct cost benefits is considered for elimination. At Raytheon, the waste of waiting was a low priority initially, mainly because it was difficult to assign specific costs to this type of waste. However, the waste of waiting is very important to the performance of the manufacturing system.

If a single focus on eliminating waste through applying Lean principles produced limited lasting success for Glenrothes, then can QRM with its focus on lead time provide a better driving metric? This was tested in the second half of the internship. The focus of the team switched to reducing lead time as the primary metric. The time it took for a circuit board to begin processing to the time it was tested and placed into shipping became the most important measurement. Any changes that were implemented were gauged on this measure.

This raised the waste of waiting to the highest importance at the expense of the other wastes such as unnecessary movement of employees and unnecessary transport of materials. The waste of waiting was nearly ignored in the initial lean implementation effort, so the shift to a lead time focus required a significant shift in mindset. The question that now had to be asked about each step of the production process was not "where is the waste here?" but "why is this product waiting here?"

One benefit to this shift to a lead time focus was that there was a simple and direct measure of the improvement team's performance: circuit card lead time. This could be calculated weekly and allowed for very good tracking of progress. A meaningful goal could also be set. The team set one week as the intermediate goal for lead time in assembly and test.

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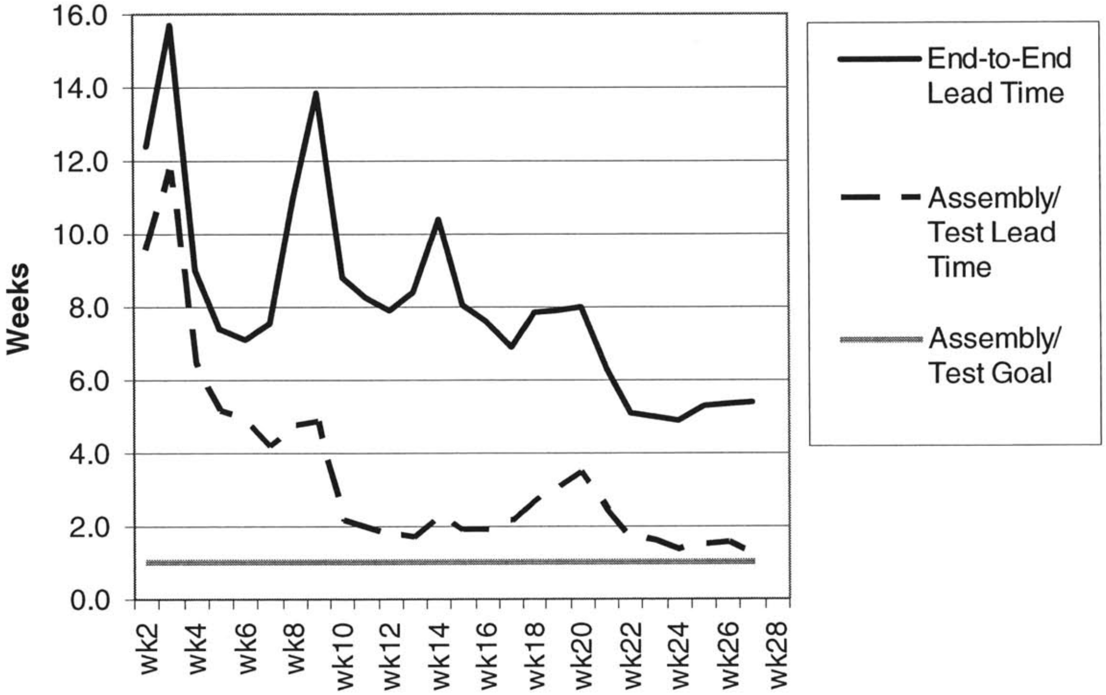
[28] Capacity buffers are maintained by keeping key machine or workers idle some of the time. This is considered waste to Lean thinkers and should be eliminated.

Choosing lead time as the goal did not in itself create improvement, but the change in mindset set the stage for significant improvement as other parts of the QRM methodology were implemented. The specifics of these changes are discussed in Chapters 4 through 7, but the end result was significant improvement for Glenrothes Circuit Card manufacturing. The lead time chart in Figure 5 shows the progress towards lead time improvement within circuit card assembly.

Figure 5: CCA Lead Time Trends



The switch to a lead time mindset led the team to follow up with the implementation of other QRM principles that resulted in sustained lead time reduction. The specific changes that led to the decrease in Assembly/Test lead time and the resulting accomplishments are explained in detail in Chapter 9.2.

4. Factory Organization

The first significant changes to be made within circuit card assembly after some initial focus on waste was to the organization of the factory. This is the subject of Chapter 4.

4.1. Product Grouping

There are two extremes within a manufacturing environment for designing product groups or families. On one extreme is finding groups of products that have nearly identical processing steps and then dedicate equipment for each one of these product families (the product family approach). The other extreme is to group the machines by department and then allow every product the ability to travel through any process step (the functional or work center approach). There are different criteria for deciding which end of the spectrum is better for the manufacturing system. These include desired flexibility, equipment availability, and product similarity.

The work center approach allows for the most flexibility because any product can go through any piece of equipment. When demand varies between products, capacity can be shared. For example, suppose three equipment groups are setup for three product families (A,B,C). Then suppose total demand for the three products is consistent at 300 per week, but the mix changes so that during any given week one of the families account for 50% of demand while the other two products account for 25%. In this case, capacity of 150 units is required for each equipment group (450 units total capacity). If the work center approach is used, then only 300 units of weekly capacity are needed.

Equipment availability is important when the production equipment is a significant capital cost and there is not enough existing equipment to setup the required groups. The benefits of families must be weighed against this additional cost of equipment. Product similarity is the basis for setting up families, so the more alike the processing of each product, the more easily families can be set up.

Lean and QRM both favor the product family approach. From the Lean perspective, only when a production line can be run with a specific set of machines that process parts with similar processing times on each machine can a true flow and pull be implemented. But Lean does not provide any answers when, for reasons of required flexibility, equipment cost, or product dissimilarity, product families are not feasible. Mixed-Model Lean is the best resource for dealing with dissimilar products, but Duggan states clearly that the processing times must be within 30% of each other for each step in order to create a Lean flow line in a mixed-model environment.[29] In many production systems, including circuit cards in Glenrothes, this is not the case for the majority of products.

QRM, on the other hand, does not place these restrictions on product groupings. QRM advocates product families for products that run on similar processes, even when these products have very different processing times and have different routings within the machine group.

In the case of Glenrothes Circuit Cards, two main product groups were identified within the entire circuit card portfolio. One product group (Product Group B) was associated with

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[29] Kevin J. Duggan, Creating Mixed Model Value Streams, (New York, Productivity Press, 2002), 37

Customer B, while the other product group included all of the circuit cards in production prior to the consolidation (Product Group A). These groupings were influenced heavily by the equipment available in circuit card assembly. For most processing steps there were two identical pieces of equipment. Separating the products into even smaller groups would have required a third set of equipment (testers, flow solder machines, assembly benches), which was cost prohibitive. The creation of these groups affected flexibility only to a small degree because most of the equipment had significant excess capacity.

4.2. Physical Layout

When constructing the physical layout of where machines will sit and where people will do their work using Lean principles, three specific wastes dictate the decisions: unnecessary transport of materials, inventories more than the absolute minimum, and unnecessary movement by employees during the course of their work. With these wastes as the guidelines, the layout should be such that products travel the minimum distance from the beginning of the process to the end. This usually results in the machines required to produce a group of products being located as close as possible to one another. Because inventory is kept at a minimum, little floor space needs to be dedicated to inventory storage.

Typically a Lean layout will take two forms: a flow line or a cell or series of cells. Both of these types of layouts have the characteristics above with the machines and work stations located close to each other. In a flow line, the machines are arranged in a linear fashion. Product flow starts at one end of the line as passes (with as little distance possible) straight onto the next machine and so-on until the end of the line. Auto assembly lines were created in this manner by Henry Ford for Model T production, and the assembly lines at Toyota are laid out in very much the same way today. Often these flow lines are accompanied by automated equipment that carries the product from machine to machine, sometimes without stopping.

The second approach, cellular manufacturing, is typically designed around a small group of workers responsible for a portion of the manufacturing of a product or a particular subassembly. To minimize the distance workers must travel, these cells are usually laid out in a "U" shape. Often many machines can be tended by one operator with very little inventory between each step. Cells can be located adjacent to one another for products that require many process steps so that the exit of one cell is right next the entry of the next cell.

Quick Response Manufacturing pushes for cellular manufacturing as the best layout. QRM has different reasons than Lean for favoring this approach, however. QRM is not that concerned with how far the product must travel or how must wasted motion an operator expels, but rather believes that cells create the best environment for minimizing lead time. For QRM, this results from the ability of operators who are in a particular section of the overall process to communicate as easily as possible and to manage the workload for their steps of the process.

QRM also has a much looser definition of cells than does Lean. A Lean cell must be balanced so that each step is closely matched to the takt time[30] for a product. A Lean cell cannot contain a mix of products unless the different products require very short changeovers and have very

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[30] The takt time in units per time period (e.g., units/hour) for a given product is calculated by taking the product demand for a given time period divided by the production time available in that same time period.

similar processing times. Also, it is very difficult to handle reentrant flow in a Lean cell (product circling back through the same process more than once).

It is much easier to create a QRM cell. Products do not need to march through the cell at a takt time or follow the same path through the cell. Reentrant flow is allowed. A mix of products (as long as they all can be produced with the equipment in the cell) is acceptable. The benefits of the cell are the close communication and ownership created amongst the operators. They now own the input and output of the cell instead of just working on whatever comes in front of their machine. Because they own the input and output to the cell, they can have a very big effect on the lead time through the cell. Cells should be large enough that they encompass a good number of process steps (the more complete a product exits from the cell, the easier it is to create a sense of ownership within the cell team.) The cell should be small enough so that the team does not become unwieldy and they start to lose a sense of team ownership. Suri recommends that the cell's team is best kept under 10 and should never exceed 15 members.[31]

We can now return to the four key production characteristics of mix, volume, demand variability, and degree of customization and see how these affect the choice of factory layout. If all the characteristics favor a Lean implementation, then the choice is between a flow line and cells. Both of these will produce the same end results, so which one of these is selected is not critical to achieve good manufacturing performance.

If the characteristics favor a QRM implementation, then the QRM cell approach is warranted. Both Lean and QRM favor some form of cellular manufacturing, so Lean and QRM are not as opposed in their factory layout recommendations as in other areas. For a manufacturing system that falls between Lean and QRM on the key production characteristics, there is a key insight to factory organization. As one moves away from the Lean-suited system (mix increases, demand becomes more variable), the strict cell approach where steps are balanced normally would rule out the cellular approach. But QRM provides the option of creating cells even with a mix of products with different routings, and still reaping significant benefits.

This point is demonstrated clearly within Circuit Card Assembly at Glenrothes. Before explaining the eventual implementation of cells, the attempt to create flow lines is explored.

Circuit Card Assembly at Glenrothes is a definite high-mix environment, meaning there are many different products that follow different routes through the factory and take different amounts of time to process. Facing this type of production, setting up "flow" is a daunting task. Ideally, processes would be setup one after the other and each board would be processed at the takt time of customer demand through each process. This is impossible in a high-mix environment like Glenrothes CCA without a complete redesign of a majority of the products. Some boards take as little as 1 minute at one stage, while others take 3 hours through the same stage. Total processing time for each board ranges from 5 minutes to 6 hours. Some boards only require 2 processing steps, while others need 13. The first recommendation from the Lean literature in cases like this is to look for product families that do share similar routings and processing times.

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[31] Suri, 1998, 477

When faced with the daunting task of creating flow, the Glenrothes team did their best. Equipment was located close together and was placed so that the product generally moved from one end of the building to the other. Within the most manually intensive assembly part of the process, a flow line was setup according to Lean philosophy. Instead of one person working on the same circuit card and completing all the required assembly himself, the station was broken down into four stations with four operators. The work was balanced through time studies for most board types so that each operator had about the same amount of work to do. Standard work was created to make the tasks less operator dependant.

The initial results of this flowline were positive from the engineers' and management's perspective. Productivity improved because operators were now focused on a smaller chunk of the total operation, and problems along the line surfaced quickly. These are the benefits that usually occur when a Lean flow line is implemented.

This part of the circuit card assembly process then drew the attention of the Lean "experts" in the factory who were well versed in the mechanics of a flow line. Many improvement ideas were offered. When operators sat idle, engineers would notice and redo the standard work sheets to improve the line's balance.

Because over 35 products each week had to run through the same flow line, the flow only operated within a batch of boards (batch quantities are addressed in Chapter 5). Between board types there was downtime when boards of different takt times were run back-to-back.

This initially appeared to be a Lean success. Product flow was improved in this part of the process. However, a more thorough analysis provides a different conclusion. This specific assembly stage was only one of an average of seven processes for a particular circuit card. In addition, only 60% percent of all circuit cards even passed through this step. The process from end-to-end was still nowhere near true flow. The other processes still operated on a push principal where work was moved to the next station to wait (usually days or weeks) for the next step to become available for processing. Some waste was eliminated within the manual assembly step, but very little impact was made to the entire system. End-to-end flow is required to reap significant benefits of a Lean implementation. In the case of Glenrothes, this type of flow was not achievable.

Without the ability to implement end-to-end flow, we next turn to QRM to see what layout is recommended for Glenrothes. QRM principles call for the implementation of cells without getting hung up on the need for flow. Each cell should contain one product family and as many of the production steps as possible should be included in the cell without making it unwieldy (more than 15 team members).

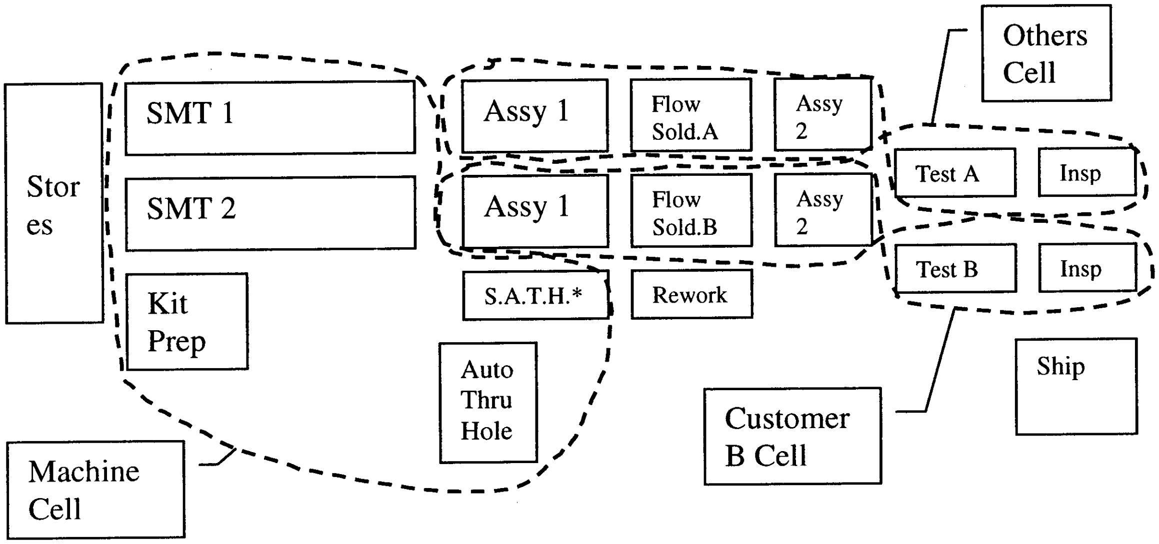
Two product families were identified in Glenrothes, Family A and B. Two cells split along these lines seem to be the ideal solution, but two aspects of the circuit card production make this difficult. The first is that there is one machine available for some types of automated equipment required to produce boards in both families. This makes it impossible to dedicate the right equipment to each product family cell for end-to-end production of the circuit card. The second issue with only two cells is that each cell team would contain nearly 20 members, which is above the ideal maximum number of 15.

A solution to both of these problems calls for splitting production into three cells, two for each product family in manual assembly and test (referred to as assembly/test cells), with one cell for both product families for automated and semi-automated assembly (referred to as the machine cell).

Initially, no equipment was moved in order to create these three cells. The existing layout, created to optimize "flow", actually fit pretty well with the two assembly/test cells and the one machine cell. The existing layout along with the new cell structure is shown in

Figure **6**.

Figure 6: CCA Layout with Cells



*Semi Auto Thru Home

This layout is not ideal because the cells are not optimized around the cell team members. They are laid out in a "flow-line" manner, which results in a long, narrow cell. Also, the two assembly/test cells overlap. A better cell layout would have the machines and benches setup around the operators, with a U-shaped design being optimal. Some of the equipment in the assembly/test cells was difficult to move[32], so the cells were initially created without any significant change to the layout.

Because each product family now had a dedicated cell area in assembly/test, it became easier for everyone to know who was working on what. This also facilitated communication between cell

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[32] The wave solder machines had fixed ducting into the ceiling to evacuate fumes.

members. By dedicating equipment to each cell, there were no disputes over which product family had priority on certain equipment. The cell leader had authority to best utilize the equipment for her specific family.

4.3. Organizational Structure

Lean and QRM share similar beliefs on the right type of organizational structure to achieve better manufacturing performance. Traditional manufacturers operate in a hierarchical structure where a group of operators is managed by a supervisor, who then reports to a manager, who has managers to report to above him/her. After this type of structure has been in place for a while, operators rely more and more on supervisors to make decisions, and supervisors in turn lean more on their managers. This creates an "I just do what I'm told" mentally on the factory floor with no sense of ownership over the production process.

Both Lean and QRM recommend turning this top down management style on its head. In a Lean factory, the first-level worker is given the most focus. Supervisors, managers, and engineers are there to support the operators. Operators are then expected to make decisions and be responsible for their output. They also are the focus of continuous improvement, instead of ideas coming just from supervisors and engineers. QRM also believes in creating a sense of ownership among the front-line operators, which is one the main benefits of the cellular approach.

In a Lean implementation, a restructuring of the organizational structure usually coincides with the physical changes on the factory floor. Operators can be trained on Lean principles: how to look for waste, the process of continuous improvement (kaizen), and building quality into the product. What if the environment is not suited to a Lean implementation? If flow and pull cannot be created, then can operators not still just be trained on these principles? The problem is that training operators on kaizen and muda-elimination in a functional environment will not make significant improvement to the overall process and will not engender much ownership. Groups of people working to improve each functional area and find isolated wasteful activities will not lead to systemic improvements. Typically the biggest problems are not solved by improving each process in isolation, but in understanding the problems with the system and attacking the highest-leverage opportunities.

QRM supports cells that encompass as much of the end-to-end production of a product as is reasonable to keep the cell members under 15 people. Operators come to understand the many steps in the process and find solutions that are best for the overall cell, not just one machine or group of machines.

The insight here is that trying to implement a Lean culture in an environment that does not fit with Lean on the four key production characteristics will not be very beneficial. Reorganizing into loose QRM-type cells first, then giving these operators a sense of ownership before asking them to make improvements, is the recommended approach.

This is just the approach taken in Glenrothes. The creation of cells broke the operations into three groups instead of one large group. Instead of 45 people reporting to one supervisor, around 15 people were assigned to each of the three cells. Figure 7 and Figure 8 show the CCA organization before and after cells were introduced. These are not meant to show relative location of equipment, but rather represent the movement toward a cellular organization.

Figure 7: Organization Before Cell Implementation

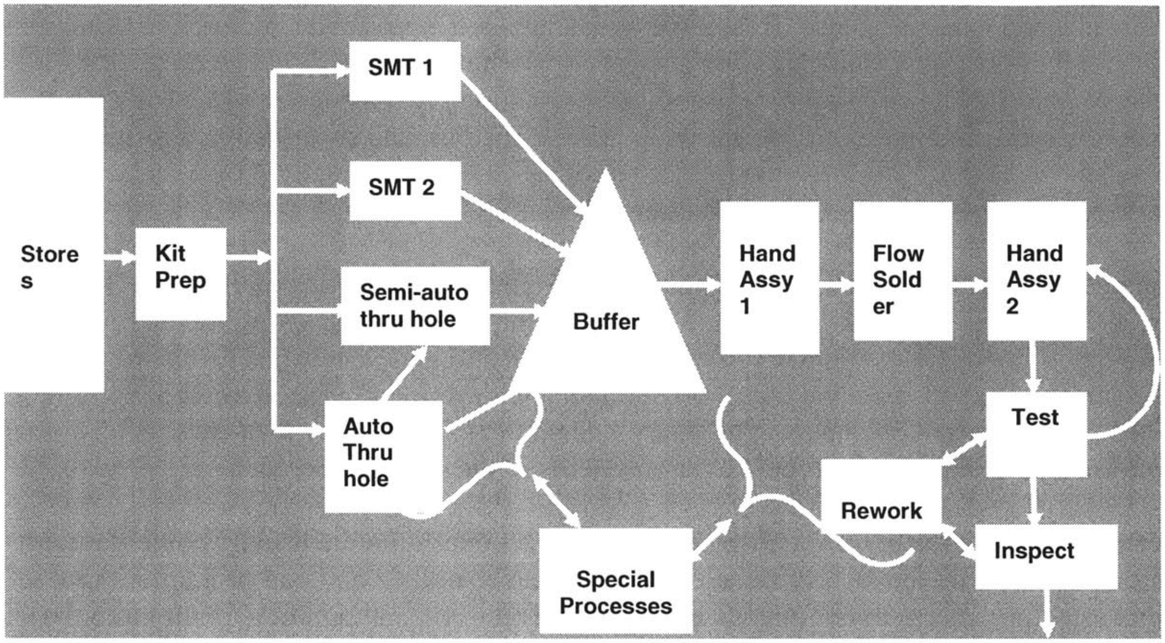
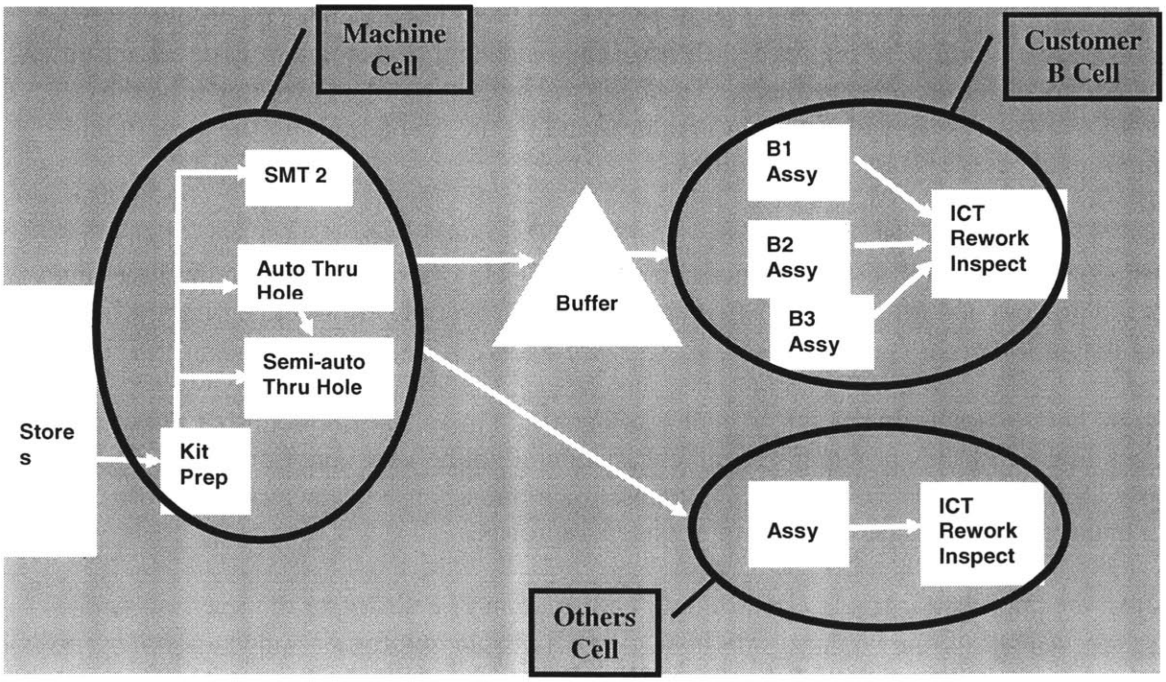


Figure 8: Organization After Cell Implemenation



It became very clear who worked in what cell, so the labor capacity became much clearer and easier to manage. Granted some flexibility is lost when labor is committed to each cell, but the advantages to the cell approach far outweigh a small loss in flexibility.

After the cells were created, teamwork and ownership began to grow within the cells. This was helped a great deal by daily morning meetings with the operators and key support personnel. At these meetings, important topics such as progress towards weekly output goals, quality problems, and that day's workload were discussed. People who had never really spoken to each other before, such as assembly operators and quality inspectors, began talking about defects on specific boards and the possible causes.

These meetings took place around the visual inventory control board described in Chapter 6.2. Since this information was located right in the middle of the cell, and the inventory locations had to be updated frequently, it became the focal point for cell information and communication.

Initially there was nearly a three week backlog when the cells were created. Before setting up the cells and the visual inventory board, the operators did not really know if they were ahead or behind schedule. This backlog was steadily whittled away as the team came together and worked to bring it down every day.

Quality started to improve with all the communication and information exchange between quality engineers, operators, inspectors, and reworkers. Attitudes of everyone involved in the production process became more positive. As the backlog went down, team members saw the light at the end of the tunnel. The changes brought positive management attention. A real team culture started to emerge in the cell, and everyone seemed to be enjoying their jobs a little more.

5. Lot Sizing Decisions

The size of the batches for each different product type in a factory has a significant effect on the performance of the plant. Inventory, lead times, and throughput are very dependent on the selection of batch or lot size.

5.1. The EOQ formula

Basic operations management theory provides a simple way to calculate the right lot size for a product. This is called the Economic Order Quantity (EOQ) or Economic Batch Quantity (EBQ). The effects of lot size on inventory quantity and setup costs are the basis for this EOQ formula. As lot size increases, inventory quantity in the factory increases in a linear manner. Increasing lot size also decreases setup costs in a non-linear manner. There is a lot size for every product and machine combination that optimizes the tradeoff between setup costs and inventory carrying costs and minimizes total production cost. This is scaled by the production volume to produce the EOQ formula[33]:

$$EOQ = \sqrt{\frac{2 * (AnnualVolume) * (SetupCost)}{InventoryHoldingCost}}$$

5.2. Lot Size of One

Lean Manufacturing discards the EOQ formula for a drive towards a lot size of one unit. The EOQ formula indicates that this should cause increasing total costs (due to the increasing setup costs outpacing the inventory cost reduction.) However, the reduction in lot size in a Lean implementation must include an associated reduction in setup costs. This even has its own acronym (SMED, Single Minute Exchange of Dies) described by Shingo[34] and perfected at Toyota. If the setup time and resulting cost gets small enough, a lot size of one will become optimal even under the EOQ formula.

5.3. Effects of Lot Sizes not Considered by EOQ

One major effect of lot sizes is recognized by both Lean and QRM but is not included in the EOQ formula: the cost of poor quality due to large batches. Quality checks are often not possible when a batch is being processed until that batch has finished. The larger the lot size, the more product is put at risk for poor quality.

Three other effects of large batches are described in QRM literature.[35] The first effect is the cost of long lead times. Long lead times leave large amounts of WIP on the production floor and increase chaos. This requires more management to coordinate than a system with very short lead times. This effect is left out of EOQ.[36]

The second effect described by QRM is the market value of responsiveness of a short lead time. In some markets, a producer with a short lead time has a significant competitive advantage over

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[33] Edward A. Silver and Rein Peterson, Decision Systems for Inventory Management and Production Planning 2nd ed., (New York: John Wiley & Sons, 1985), 178

[34] Shigeo Shingo, A Revolution in Manufacturing: The SMED System, (Portland, Ore.: Productivity Press, 1985).

[35] Suri, Quick Response Manufacturing, 1998, 176

[36] Ibid., 177

one with a much longer lead time. This has actual monetary value to a company but is also not included in EOQ.[37]

The third effect is an increasing Response Time Spiral, which was described in Chapter 2.2. A long lead time causes missed shipments, which leads management to promise longer lead times to customers in order to meet on-time delivery. Lead times creep up over time as management focuses on process efficiencies without regard to effects on lead time, and the cycle repeats again.[38]

A fourth consideration that the basic EOQ formula ignores is the interaction between multiple products on a single resource. For example, suppose four products are produced on Machine A. Each product has a setup time of four hours and processing time of one hour. Demand requires that four of each product on average are produced each day, and the machine is available 20 hours per day. The EOQ formula could easily produce an optimal batch size of four by balancing setup and inventory costs, but this produces an unfeasible solution because this would require 32 hours in a day of machine availability (16 for processing and 16 for setup).

This capacity issue is addressed by the Lagrangean method described in an LFM thesis by Kletter in 1994.[39] But even this method has its shortcomings. It assumes deterministic processing and setup times, but in reality these always have some variability. This variability causes the capacity limit to be reached sooner than in the deterministic case. An arbitrary capacity limit can be chosen to better account for this (e.g., using 90% of maximum capacity). This method also just addresses the capacity issue, not the cost of poor quality, cost of long lead times, and costs of a growing response time spiral.

5.4. QRM Optimal Lot Size

QRM takes a much more holistic approach to the lot size question. It finds a middle ground between the EOQ's tendency for large batches and Lean's mantra of "lot size of one". QRM takes into account process & setup variability and limited capacity in determining an optimal lot size. The general case is shown in Figure 1 for one product. Because QRM's focus is on lead time reduction (and all its associated benefits), the response plotted on the Y-axis is lead time.

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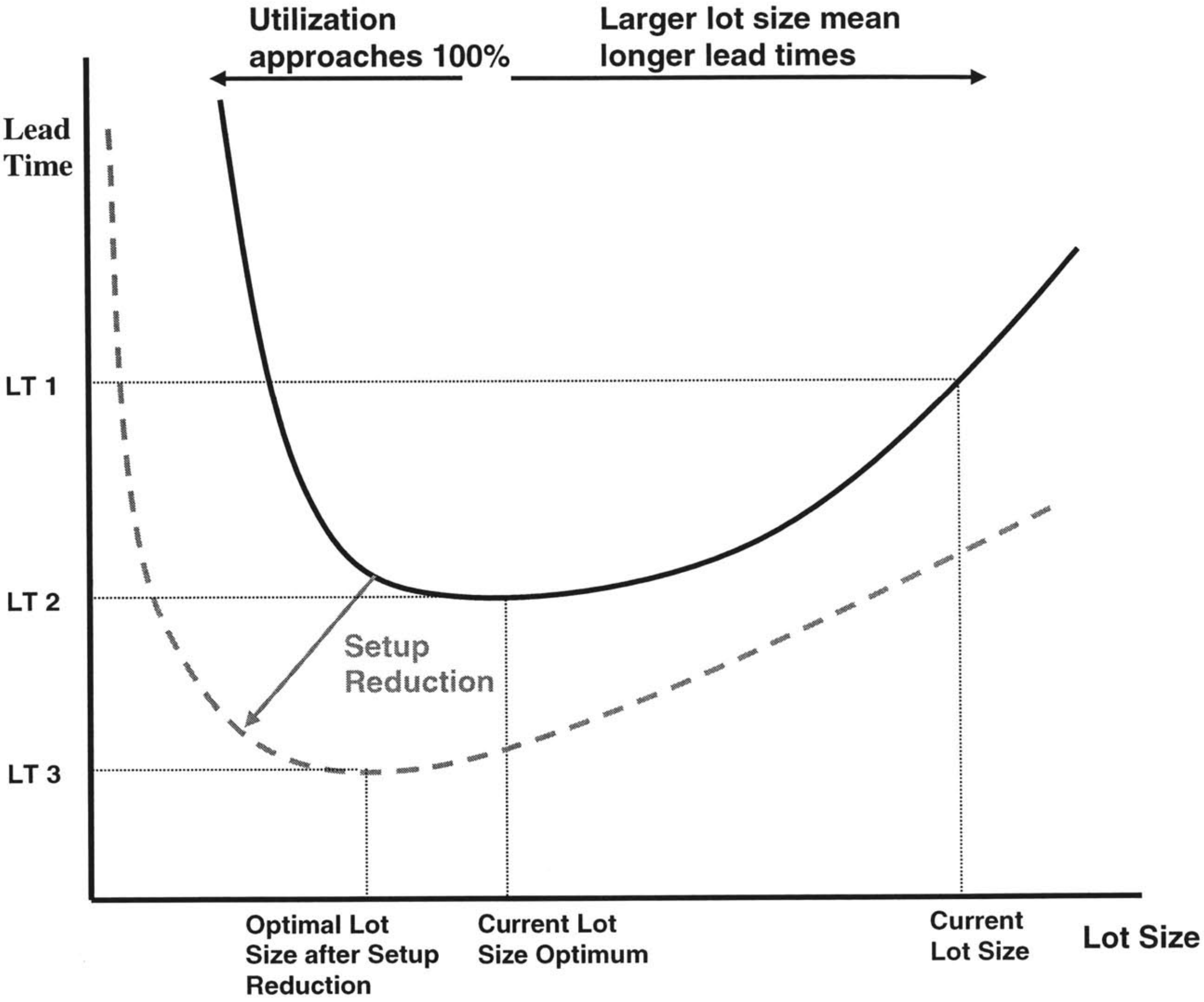
[37] Ibid., 177

[38] Ibid., 177

[39] Details of this method can be found in lecture notes from MIT Course 15.066J Summer 2002 taught by Professor Steve Graves.

Figure 9: Lot Sizing/Setup Effects on Lead Time



For a production environment that fits QRM very well, choosing lot size based solely on optimal lead time is appropriate. It will produce a batch size somewhere between that given by EOQ and Lot Size of One. In a mixed environment such as Glenrothes circuit cards, however, the choice of the right lot size does not entirely fit any of the paradigms: EOQ, Lot Size of One (Lean), or Minimum Lead Time (QRM).

5.5. Lot Sizes in Circuit Card Assembly

The improvement team at Glenrothes first addressed the lot size question fairly early in the project. Here the team deviated from a strict Lean perspective and decided on two separate approaches for choosing lot size, one for the automatic SMT machines, and another for non-SMT processes. For products that were produced with SMT machines, the EOQ formula was used to determine a standard lot size for each product. This was actually a significant improvement over the existing lot sizes, which were much higher than those calculated using EOQ.

For products that were not produced on the SMT machines, and also for the downstream manual assembly of circuit cards that first went through SMT, a different lot size decision-making strategy was used. At this point in the project, nothing was known about QRM, so the only guidance on lot size for the team was either to use EOQ or to push towards lot size of one. Fortunately the team realized that a lot size of one in the assembly and test areas would be disastrous for the simple reason that there was not enough capacity on the testers or flow solder machines to changeover between every product. A quick calculation was performed that suggested an average lot size of nine would easily allow all processing and setups to be performed at flow solder and test without running into a capacity issue. Products with lower volume were assigned a lot size of 6, while higher volume products were assigned a lot size of 12.[40] This may seem rather arbitrary, but these choices were not so bad in hindsight.

The heuristic method just described is very unlikely to be optimal in a high-mix, low-volume environment. Once the driving metric used for the improvement in circuit card manufacturing was shifted to lead time, lot size was revisited. If lead time is the driving metric, then the QRM lot size calculation should be the best of the three options. But CCA production deviates from one of the key QRM assumptions: that shorter lead times create significant additional market value. In the case of circuit cards, demand is known some time in advance. Customers can usually provide accurate forecasts of their demand a month ahead of time. This means that reducing lead time beyond a certain point will not continue to create additional value to the market. Once an acceptable lead time is reached, further reduction will have other benefits (quality, reduced chaos), but not additional market value. This logic leads to the conclusion that the optimal lot size for Glenrothes CCA is somewhere between the QRM optimal lot size and the EOQ formula.

Another complicating factor in the lot size decision for Glenrothes is the many different processes that each product travels through. Which process step (automated assembly, semi-automated assembly, manual assembly, or testing) should determine the lot size? The question was simplified in Glenrothes by looking at the machine cell and the assembly/test cell separately and attempting to select the right lot size for each cell.[41]

The project team was not able to address the validity of EOQ-determined batch sizes in the machine cell by the time the internship finished. The optimal batch size for the assembly/test cell, however, was analyzed at length, so the lot size decisions in this part of the process can be discussed.

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[40] The team was interested in choosing lot sizes that were both easy to breakdown (12-6-3-2) or were easy to run higher multiples in SMT (24, 36, 48)

[41] The cell structure is described in Chapter 4.3

Figure 10 shows the optimal lot sizes for all boards in Family B based on the EOQ formula, along with the lot size implemented after two months into the internship. The corresponding optimal QRM lot size could not be calculated because some of the factors that go into this calculation were not readily measureable.[42]

Figure 10: Assembly/Test Lot Sizes and EOQ

Board Number	Monthly Demand	Assy lot size	Assy EOQ
Product 1	24	24	33.3
Product 2	8	6	4.7
Product 3	8	6	4.4
Product 4	6	6	3.9
Product 5	24	12	11.7
Product 6	14	12	10.4
Product 7	8	6	5.3
Product 8	14	12	5.0
Product 9	4	6	1.9
Product 10	60	12	14.4
Product 11	14	12	7.9
Product 12	14	12	12.4
Product 13	14	12	18.7
Product 14	2	6	3.1
Product 15	8	6	15.5
Product 16	60	12	10.7
Product 17	2	6	1.6
Product 18	12	12	4.4
Product 19	20	12	5.8
Product 20	4	6	2.7

Board Number	Monthly Demand	Assy lot size	Assy EOQ
Product 21	20	12	5.5
Product 22	8	6	4.5
Product 23	6	6	3.5
Product 24	14	12	6.1
Product 25	14	12	4.5
Product 26	8	6	3.8
Product 27	2	6	1.6
Product 28	12	12	4.4
Product 29	14	6	3.6
Product 30	2	6	1.8
Product 31	12	12	4.7
Product 32	6	6	3.3
Product 33	18	12	7.3
Product 34	6	6	1.6
Product 35	8	6	4.0
Product 36	4	6	1.5
Product 37	18	12	2.9
Product 38	8	6	11.4
Product 39	20	12	6.1

Without knowing the QRM optimal lot size, the range of potentially optimal lot sizes for each product (between the EOQ and QRM optimal) cannot be calculated. The optimal lot size then must be empirically determined. During the internship, the only attempt at modifying lot sizes after the initial values were set using EOQ for SMT and 6 or 12 for non-SMT products was to follow a heuristic recommended by Suri. This "QRM nugget" recommended that the total processing time plus setup time of each lot should be similar between products to reduce variability.[43] With this guidance, the products with the longest total batch processing times were cut so that no batch had a total processing time above 15 hours. Only 5 products out of 60 had their lot size reduced. This change did not correspond to a noticeable change in lead times, which indicates that these products were somewhere near the optimal lot size already. In this region, a change in lot size will not produce a significant impact on lead time (refer to Figure 9).

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[42] Suri, 1998, 162

[43] Suir, 1998, 175

It is also important to note that the products whose lot size was not changed have a significant impact on the lead time of products whose lot sizes were decreased. Since only 8% of the total volume of Family B saw a lot size change, it is not surprising that lead times did not measurably decrease.

5.6. Lot Size Discussion Summary

The best takeaway from this discussion on lot size is that there is much more to this decision than simply computing an EOQ or setting a lot size of one. QRM accounts for factors not included in the EOQ, but with a high-mix of products the optimal lot size is still difficult to accurately determine.

The one thing EOQ, Lean, and QRM all agree on regarding lot sizes is that reducing setup times will allow for a corresponding reduction in optimal lot size. Efforts to cut setup time will lead to more improvements than tweaking lot sizes. This is the recommendation going forward for Glenrothes. The improvement focus should be on reducing setup times on SMT machines and the assembly/test equipment to allow for smaller lots.

6. Production Control Strategy

Once the factory has been organized and lot sizes chosen, the next step is selecting and implementing a method of controlling the movement of product through the production system. This is referred to as a production control method.

6.1. Lean Production Control: Kanban

In a Lean production system, material flow is pulled through the processes with the use of Kanban cards. These cards are limited and therefore put a cap on the inventory in the system. A Kanban driven system requires all processes to be working well. It forces improvements to be made to less reliable processes in order to keep product flowing.

In a low-mix, high-volume, low-demand-variability, low-customization environment, Kanban is a well-suited production control system. As the manufacturing environment deviates from these four characteristics, the appropriateness of Kanban comes into question.

As mix increases, the Kanban system becomes more complex with a set of cards needed for each product. This can be mitigated by a generic card that covers multiple products, as long as these products have the same routing and similar processing times at each step.

As volume decreases, an interesting drawback to Kanban arises. Kanban requires at least one unit of inventory to remain between each process step for each product. For a high-volume, low-mix operation, this added inventory is trivial. In the case of Glenrothes CCA, there are 100 different product types with an average of 8 processing steps. The average batch size is 9, so to create and maintain a Kanban system, 100x8x9 = 7,200 boards of inventory would be needed. Since monthly demand is only 1,200 boards, this amounts to six months of inventory on the factory floor! If batch size could be cut and some processes could be aggregated, the inventory requirements would drop. However, they would still be much higher than what most would call "Lean".

How does Kanban fit with high demand variability and high customization? Kanban is better suited to low demand variability where the number of cards (and thus maximum inventory) remains constant over time. Kanban can be modified for demand variability by revising the number of Kanban cards as demand changes. This may defeat the goal of simplicity in a Kanban system, but is the price paid for demand variability.

High customization is even more difficult for a Kanban system. A Kanban card identifies a specific product with a standard bill of materials and routing. Customization implies a non-standard BOM and possibly routing as well. New Kanban cards would have to be created for each new customized option. The more customization increases, the less Kanban fits the system.

6.2. Production Control Strategy for Glenrothes

What is the best production control strategy in a high-mix, low-volume environment? Before evaluating the strategies mentioned in the Literature Review Chapter 2 (CONWIP, POLCA, DBR), a modified pull system developed in Glenrothes is explored.

6.2.1. Modified Pull in Circuit Card Assembly

Prior to the beginning the internship, Glenrothes CCA operated in a "push" style of production control. Orders were received from the customer, and these boards were moved onto the floor and worked their way to the end of the line as capacity allowed. This led to 12 weeks of inventory accumulating on the floor and late orders to customers.

In an attempt to follow the Lean roadmap and to implement pull, the internship team set up two buffers within CCA assembly. The first was between the machine section and manual assembly. The second was between the end of Glenrothes production and the beginning of the customer's production. Production would be triggered upstream of each buffer only when the level of inventory for a particular product in the buffer fell below a specified level. This trigger level averaged four weeks of inventory, which seemed reasonable assuming that product could be produced in two weeks time. Between buffers, product still moved in a "push" mode. This was an improvement over the old system that was 100% push, but it was still not an ideal solution.

Because product was pushed between buffers, there was no real control over total inventory. If capacity was not maintained at an adequate level, inventory could grow unchecked. An increasing level of WIP leads to increasingly longer lead times by definition under Little's Law (Average Lead Time = Average WIP/Average Throughput).

6.2.2. Production Control Alternatives

Could another production control strategy (CONWIP, POLCA, DBR) offer a solution? There were two levels of production control needed after the reorganization into cells: a higher level that would control the movement of circuit cards *between* cells, and a lower level that would control movement *within* cells.

For production control between cells, the two alternatives were the pull system that Glenrothes had implemented, or the POLCA method favored by QRM. POLCA's advantages as explained in Suri's book would be limited in Glenrothes. Circuit Card Assembly only operates with three cells – one upstream cell feeding two downstream cells. Creating POLCA cards for every type of circuit card, then evaluating regularly how many cards should be in circulation, would be a significant management task. Another option with POLCA would be to create cards that were generic to a batch of circuit cards. But because the batches differed so much in the amount of processing required within each cell, these generic cards would not be very effective.

The final conclusion is that while POLCA might offer some advantages, the pull system that was already in operation was nearly as good and the entire infrastructure needed to operate this system was in place. A trial using generic POLCA cards could be conducted for a period of time as an experiment to compare to the existing pull system, but lacking this data a witch to POLCA is not justified.

For production control within the cells, one specific cell at Glenrothes is the basis for discussion, namely the Family B assembly/test cell. Four methods are considered: traditional push, a modified form of push that can be termed visually-controlled push, CONWIP, and DBR.

Traditional Push

Traditional push operates by allowing product to move to the next processing step without any checks or limits. Product reaches a processing step and is completed (usually first-in, first-out). With this type of production control, inventory can grow unchecked, which in turn allows lead time to grow unchecked.

Visually-Controlled Push

An alternative to traditional push is a version of push that can be called visually-controlled push. In this type of system, product is still pushed from step-to-step, but the key difference from traditional push is that there is a good mechanism to monitor inventory and capacity at each processing step within the cell. Also, decisions can be made quickly to move capacity (in this case labor) to the appropriate part of the cell. This information can be kept electronically, monitored closely by the cell team itself, or monitored by the cell lead or supervisor.

Glenrothes implemented this type of modified push as the production control system within the assembly/test cells. The centerpiece of the system was a large whiteboard placed in the middle of each cell that contained all of the products made in the cell along the left and all the possible processing steps along the top. This created a product-process matrix for the cell. There was also a column for due dates for each batch of boards. A simplified example of this "inventory-control" board is shown in Figure 11.

Figure 11: Inventory Control Board

Today's Date: Wednesday, Aug. 10

		Process Step											
Board No.	Due Aug. 15	Machine A	Machine B	Machine C	Assy A	Assy B	Assy C	Test A	Test B	Inspect	Rework	MRB	Ship
Product 1	6	▨	6	▨			▨		▨				
Product 2	12				12		▨						
Product 3	12	▨	▨					▨	9		3		
Product 4	6			▨	▨	▨	▨		▨	10		2	
Product 5	12	▨	▨	▨				▨					12
Product 6	6			▨	▨					6			
Product 7	6	▨	▨	▨				▨		4	2		
Product 8	12	▨	▨	▨					▨				
Product 9	12				▨	▨							12
Product 10	24	▨					12	▨	10		2		

Shaded squares indicate processing steps that are skipped for that particular product.
A number was placed in any product-process square corresponding to the quantity of that particular board type that was being processed (or awaiting processing) at that step. A quick

glance at this board could tell the team and its lead/supervisor where most of the work was located and how close it was to completion. The lead could move operators to whichever process showed a small backlog and prevent product from waiting for any significant length of time.

Daily and weekly production targets, along with any backlog, were posted right next to this inventory-control board. This also made it very clear to everyone in the cell how they were progressing during the week. Prior to this information being posted, it would take until the end of the week (Friday) to realize that production was going to miss the weekly Monday shipment. A scramble to get weekend overtime ensued, with the typical result that many shipment targets were missed come Monday.

With this system working so well, it may not seem necessary to consider alternatives such as CONWIP or DBR. But the system described above was still not stable. It relied on a lead or supervisor to constantly be on top of where product was in the process and what labor was available. If the lead and supervisor were off for a few days, or if an upset hit the system (a large order in one week or a significant amount of absenteeism in a week) inventories could start to balloon within the cell. This would lead to increasing lead times and shipments would start to be missed.

CONWIP

CONWIP would prevent the rising inventory situation just described from occurring. It would put a limit on inventory within the cell. Due to Little's law (Lead time = inventory/throughput), the average lead time would be much more consistent. The main challenge to implementing CONWIP is dealing with the high mix of boards and different batch sizes for each type.

For example, assume a complex board that had a lot size of 6 was completed and moved into shipping. The next batch of boards in line to enter the assembly/test cell is a simple board that has a batch size of 12. When this enters the cell, the net result is that the work content within the cell has decreased (a batch of complex boards was replaced by a batch of simple boards), but yet the total number of boards has increased. If we try to setup the CONWIP system so that each completed board signals the release of a new board into the cell instead of releasing in batches, then we face the problem of constantly changing batch sizes.

Drum-Buffer-Rope

The fourth option for production control with the Glenrothes cells is Drum-Buffer-Rope. First the drum must be chosen. The most predictable part of the assembly/test cell is manual assembly. Here is where we propose to set up the drum, or pacemaker. Because Glenrothes demand is known well ahead of time on most products, the drum can be scheduled ahead of time. Certain products have high enough volume that they could be scheduled weekly, others bi-weekly, and some only once a month. This would have the benefits of easy scheduling of manpower and a more predictable rotation of products moving through the assembly/test cell. Accurate daily production metrics fore each product could also be implemented for manual assembly.

Since the drum is the first step in the assembly/test cell, there is no real need for a "rope". The buffer in this case is already in place between the machine cell and assembly/test cells and part of the between-cell pull system. Downstream of the manual assembly drum, which includes test and rework, would operate in a push mode (in the case of Glenrothes, the visually-controlled push could be left in place). Excess labor capacity would need to be maintained in test and rework to ensure that surges in quality problems would not significantly affect lead time.

A CONWIP system and DBR system both have advantages over the existing visually-controlled push system. CONWIP would control inventory and keep lead time predictable but would be difficult to implement effectively. DBR would create a more predictable assembly schedule and would be easier to implement than CONWIP, but DBR still leaves the possibility of inventory buildup in the test/rework area if not monitored closely. Either DBR or CONWIP would be an improvement over the existing system, so a trial of each is recommended to determine the optimal production control method for Glenrothes circuit card assembly.

7. Material Presentation to the Line

How material is presented to the production line is not a critical component of all factory improvement efforts as is the case with metrics, factory organization, lot sizes, and production control strategy. However, because such a significant portion of the internship was spent addressing this issue, it is discussed here in some detail. There are three basic concepts concerning storing material before its use and the presentation of the material to the line: point-of-use, central stockroom, and kitting. These are not mutually exclusive in all applications, but they will be described first as distinct strategies.

7.1. Three Material Presentation Strategies

Point-of-Use Material

The "Leanest" of the three methods is called point-of-use. With point of use material, parts are delivered from suppliers and placed directly onto the line ready to process. There are no other staging areas or stockrooms for the material. This results in the least waste because staging areas and stockrooms just lead to extra handling. Also, the closer the material is placed to the process, the less wasted effort is required by the operator to retrieve it when needed.

Central Stockroom

In this method of inventory storage, all material is delivered from suppliers to a common location. When material is needed on line, it must be retrieved from this location. Depending on how far this location is from the line and the complexity of the procedures used to issue this material to the line, there can be a significant amount of non-value added work associated with this system.

Kitting

Kitting is the process of aggregating parts for a particular product or production run. In Glenrothes CCA, each circuit card has a bill-of-materials that lists all the components that must be assembled on the board. Prior to running a batch of these boards, all the components needed are pulled together in a "kit" that travels with the board through production.

Kitting can be used with either a central stockroom or point-of-use material. In a central stockroom, kits are prepared in the stockroom before a batch of products are run and then issued to the line when the product begins its route through the factory. With point-of-use, kits could be prepared by an outside supplier and delivered to point of use as a kit.

Combination Strategies

A combination of central stockroom, kitting, and point-of-use can also be used. In one scenario, suppliers deliver incoming material to a central stockroom. Point-of-use locations are setup on the line with the complete set of parts for every product (in effect, a POU "kit" for every product). These point-of-use locations are then stocked periodically from the central stockroom. Operators on the line then just grab the right POU kit when that product comes through their process. This method will be called "Kitting Before Point-of-Use."

A variation on this method is to keep point-of-use material on the line in common bins (***not*** in a kit). When an operator needs to assemble a certain product, he assembles his own kit from the bins of parts. This is actually different from true point-of-use where material is kept close enough to the operator that he can grab a part as he completes each operation without gathering (or kitting) all the parts ahead of time. The method will be called "Kitting After Point-Of-Use."

7.2. Material Presentation Analysis

According to Lean thinkers, a central stockroom is always a form of waste. Kitting is also not preferred by Lean advocates because it is an additional non-value added step in the process. The customer would not see the aggregating of parts prior to assembly as valuable. Point-of-use material has been nearly perfected at Toyota, where all components needed for the assembly line arrive just-in-time to the line in the right order. It is amazing how synchronized this entire process is with such large components like seats and engines.

As a production systems stray from the ideal Lean system characteristics (towards higher mix, lower volume, higher demand variability, and higher customization), the superiority of POU material presentation is less obvious. As mix increases, more parts at each station are required with a POU system. This makes POU more difficult. As volume decreases, it becomes more difficult to justify setting up dedicated POU locations, bins, handling equipment, etc. As demand variability increases, it becomes necessary to keep more inventory to account for swings in orders. This can present a space issue in a POU system depending on the layout of the factory floor.

As customization increases, the benefits of POU material decrease. Parts may not even be kept in stock for rarely ordered options because it is too expensive to keep every possible part on hand. In this case a point-of-use location could be specified, but it would sit empty until the special-ordered part arrived from a supplier. This is not a good use of floor space if there are many of these types of parts.

Thus the farther we move towards a QRM-suited production system, the less point-of-use material makes sense. Material presentation is not specifically addressed in the QRM literature, but the reasoning just given makes it clear that point-of-use material is not well suited to a QRM environment.

7.3. Four Additional Factors

In addition to the four key production characteristics, four other important factors must be considered when selecting a material presentation strategy. These are: Commonality, Size, Quantity, and Value.

Commonality

The first factor is the amount of commonality among components between products and processes. On one extreme, every part used in production is unique to every product. Also, no parts are shared between processes. To say it another way, each part is used on only one product and one process. On the other extreme are parts that are shared among many products ("product commonality") and processes ("process commonality").

Parts that have product commonality on a particular process are well suited for point-of-use material presentation. This actually reduces the number of different parts that must be kept next to the line.

Process commonality works against point-of-use material. If the same part is needed on multiple processes, then some compromise must be made when attempting point of use. If point of use is desired, then some quantity of the same part must be kept at each process location. This increases the amount of inventory that must be held compared to a central location for these parts.

Size

The second important factor that goes into the material presentation strategy is the size of parts compared to the square footage of the production area. As the size of parts becomes larger, it becomes more difficult to place all the inventory right next to the line. Toyota has solved this problem by creating elaborate, expensive overhead tracks that bring large components to the line. This is made possible by the consistency of the product from year to year and the large volume that allows Toyota to spread these capital costs over many units.

Quantity

In a similar vein to the factor of size, the more parts that are placed at one process, the more difficult it becomes to setup the parts at point-of-use right next to the operator.

Value

The last factor to the material presentation decision is the value of the parts. Parts that are very expensive or very difficult to replace (long lead times) are more suitable to a central stockroom. Inventory control policies are typically better in a central stockroom than at point-of-use locations. Although this is often the main argument given for a central stockroom, it is actually the weakest argument for centralized inventory. There is no reason that operators and material handlers on the floor cannot be trained to handle high value parts and take ownership of making sure inventory remains accurate.

7.4. Combining the Four Key Production System Characteristics with the Four Material Presentation Factors

We can now look at material presentation strategy from the perspective of the four key characteristics of a manufacturing system and overlay analysis using the four material presentation factors to make the best choice for presenting material to the line. As stated in the introduction to Section 3.4.1, systems that tend toward the Lean end (low mix, high volume, low demand variability, low customization) are well suited for a true point-of-use system where the right part is presented at the right process at exactly the right time. However, if the material presentation factors are unfavorable (high process commonality, large size parts, high quantity of parts per product, and high value parts), then a move towards a common stock location for these parts with kitting must be seriously considered.

7.5. Material Presentation in Glenrothes

Systems that do not fall along the Lean end of the Key System Characteristics Continuum must be analyzed further to determine the best material presentation. As in previous sections, the Glenrothes CCA line will be used for the case of a mixed Lean/QRM environment.

First, the material presentation factors of commonality, size, quantity, and value as they pertain to Glenrothes must be understood. Glenrothes has some product commonality but little process commonality. The size of most parts is small and quantities per board at each process are not very high (average of 3 parts per board), but because of the high mix it is not possible to locate parts within arm's reach of operators at each process step. The value of parts ranges widely, from fractions of a cent up to 50% of total board cost.

The internship addressed the material presentation at all of the manual CCA assembly stations for Product Family B. There certainly are material presentation issues at the semi-automated and automated process steps and with Family A, but these will not be presented in this paper.

Initially all material was held in a central stockroom and parts were kitted when an order was placed to begin assembling a batch of boards. This kit was created in two parts, a machine kit and an assembly kit. The machine kit was for all the automated and semi-automated steps at the beginning of the process. This kit was issued with the boards into the first process step. The assembly kit was for all the manually assembled parts. This kit was brought to the assembly area and placed on a shelf at the same time the board started in the machine area. This led to assembly kits sitting for weeks waiting for the machine portion to be completed before assembly was begun. It was not always clear to production which kits were associated with which batches, and operators spent significant amounts of time during the day searching the shelves for the parts they needed. In addition, many parts were lost and written off as scrap.

An improvement was definitely needed. The low variability in demand and low customization supported the implementation of POU material. The high-mix, along with issues of product commonality, created challenges to a straightforward POU implementation. There were two options available that contained a mix of POU, central stockroom, and kitting.

The first option, a form of "Kitting Before Point Of Use", maintained a central stockroom. Locations were setup within 10 feet of the assembly workstations. The parts needed for each board type were located together so that the operator only needed to take these co-located bins to her desk when she went from one board type to the next. Many parts shared product commonality, and these parts required duplicate POU locations. The most commonality was 13 out a total of the 60 board types for Family B. This led to a proliferation of inventory for these components, but it was believed that this would be the most efficient presentation of material for the operator.

The second option was also a POU solution of the form "Kitting After Point Of Use", but common parts were not kept in separate bins for each board type. There was only one location for each part. This meant that the operator was required to create her own kit prior to starting assembly of a batch of boards.

Both options were implemented in manual assembly and their effectiveness compared. Option 2, Kitting After Point Of Use, was by far the most preferred by production and stockroom personnel. The kitting that was required by the operators created a sense of ownership over materials. Shortages were less with this option because each part was only allotted one location, reducing confusion. Option 2 also was very capable of operating without a central stockroom. Option 1 could have operated without a central stockroom, but using a supplier to fill many different bins with the same item would not be trivial and would have required a more sophisticated inventory management system.

Again we see that strict application of Lean principles is not called for in every situation. In Glenrothes, a mix of point of use with operator kitting was the best fit, but it took an analysis of the material presentation factors along with some trial and error before the best material presentation strategy was found.

8. Three Perspectives on Organizational Processes

This section of the thesis analyzes the changes to circuit card assembly in Glenrothes through three perspectives, or lenses. The first is the strategic design lens, which looks at the strategy of the organization and how it is structured to achieve desired results. The second perspective is the political lens, which looks at the power structure in the organization and how informal influence is used to create (or oppose) change. The third perspective is the cultural lens, which is the most difficult to pin down but often the most important factor when attempting to affect change. Culture is the underlying beliefs and norms held by the members of the organization.

8.1. Strategic Design Lens

8.1.1. Organization Strategy

The strategy for circuit card assembly was laid out by the manufacturing manager. His intention was to grow the circuit card business, and to do this he believed that Glenrothes needed to become more cost competitive while at the same time delivering excellent on-time performance to customers. Glenrothes was the sole Raytheon site in the United Kingdom for producing circuit cards, and he wanted it to garner a strong reputation inside and outside Raytheon for its circuit card assembly capabilities. The manufacturing manager also wanted to win higher-volume business for Glenrothes. The addition of Plant B products in early 2004 doubled volume and the desire was to bring in more high-volume products (high relative to Glenrothes, but still low compared to the real high-volume circuit card manufacturers).

Three new circuit card products that would again double circuit card volume were planned for launch near the end of the 2004 and into 2005, and the manufacturing manager knew improvements were needed to the CCA department to provide the type of manufacturing performance that would make these new products successful and lay the groundwork for winning more business.

The improvement strategy favored within RSL was to use Lean Manufacturing along with Six Sigma methodologies. Lean would provide the guidelines for what needed to be done (reduce waste, implement flow and pull), and Six Sigma would provide the improvement framework (define, measure, analyze, improve, control). The circuit card improvement project was undertaken using this Lean Six Sigma strategy.

To summarize, the project was aligned with both the business strategy and improvement philosophy of Raytheon RSL. It had management support and significant resources assigned to it.

8.1.2. Formal Organizational Structure

Raytheon Glenrothes had a typical functional structure in which the major functions (engineering, production, quality, program management, supply chain) were separate groups with separate managers. Members of the circuit card improvement team were contributing members of these specific groups. Although the team members had common goals, they all reported into functional managers that did not all have identical objectives. Also, only two team members (the author and the Six Sigma expert) were dedicated full-time to the effort. The rest were giving a portion of their time along with performing their regular job in their home function.

In order to really improve circuit card manufacturing performance, this team needed to partly set aside their specific functional responsibility and contribute to the overall improvement of circuit card manufacturing. The team members as a whole were supportive of the effort and wanted the team to be successful.

Two functions in particular were not represented in the initial team structure, and this hindered the team's overall progress. The first function was production engineering, which had engineering responsibility for a specific group of products (as opposed to process engineering, who was responsible for specific types of equipment). The second function was production. The team initially had the general supervisor as a team member with little participation from supervisors, leads, and operators. The effects this had on the team and its progress are explored in Section 8.2.1.

8.2. Political Lens

8.2.1. Key Stakeholders

In order to understand the political context of the project, the interests of each stakeholder and how these relate to the project must be explored.

The two stakeholders with the most influence on the project in the beginning were the project sponsor (the manufacturing manager), and the project supervisor (the engineering manager). This project was aligned with the strategy that the manufacturing manager had laid out, so he was very interested in a successful outcome for the project. The project supervisor was also very invested in the project, but for different reasons. He was heavily involved in managing the project and leading the team, whereas the manufacturing manager was mostly hands off besides a weekly update meeting.

The manufacturing manager wanted this project to succeed in order to realize the strategy he had laid out. The project supervisor shared this motivation, but he had the additional motivation of the inherent satisfaction that would come from improving the circuit card manufacturing system.

Operations

Midway through the project, the manufacturing manager backed away from the champion role and let the newly hired operations manager fill that role. This person had strong ideas about how the improvement effort should proceed. Luckily these ideas mostly aligned with the team's direction. He did see the author's role differently than both the project sponsor and supervisor. He did not want the improvement driven by someone from the outside, but instead preferred to have Raytheon employees within his operations organization driving the improvement.

Within his group were the general supervisor, the line supervisor, three operator leads, and close to 45 operators. The general supervisor was a key member of the team from start to finish. He was a big supporter of improving circuit cards to make his life a little easier. He was always involved in fighting fires and wanted to reduce the chaos on the factory floor. This sentiment was also held by the supervisor and leads.

The line supervisor, leads, and operators were important stakeholders in the project, but were not very involved in the first half of the project. This lack of participation from production hurt the buy-in of the changes the team was trying to make. Although there was not strong opposition to changes, there also was not strong ownership and the changes that were made required continual follow-up to make sure they were being sustained. Those changes that had little follow up slowly reverted back to the old way of doing things.

Engineering
As explained in the description of organizational structure, engineering was divided into two groups: production engineering and process engineering. The two process engineers were team members from the start and gave good support to the team until their workload became excessive midway through the project. Their interests were always aligned with the team, but they became less able to participate near the end of the internship.

Production engineering, on the other hand, was not really involved in the beginning. The project supervisor made an attempt to invite the lead production engineer to the team meetings, but this group never seemed to lend strong support to the project. As the project went on it was apparent that this group felt left out of the improvement project. Asking them to attend the meeting so far into the project was seen as more of gesture than a true desire to bring in their ideas.

This slowed the progress of the team because so much of what we were trying to do needed the support of production engineering. The production engineers should have been key team members from the beginning. They are responsible for continuing with many of the initiatives after the end of the internship, so they needed to be heavily bought into the project.

Customers
The main customers were the program manager for Plant B products and two representatives at the Plant B site. The Product B program manager resided in Glenrothes and was an integral team member and strong supporter throughout the project. She was a good ally to have because she often communicated with other managers within RSL and tried to put a positive spin on the team's efforts.

The actual customers at Plant B were also very supportive of the team's efforts and were keen to see improvements at Glenrothes. Their success was tied to the team's success, and they also deflected a lot of heat from the project when things were not going great halfway through. They were implementing their own lean initiatives at Plant B, so they understood what we were trying to do. They also participated in the Glenrothes' team process by attending weekly conference calls and coming to Glenrothes once a month. Having the customers' interests aligned with the project team was a big reason why the project was eventually seen as a success within RSL.

8.2.2. Political Risks

There were not many political risks with this project. The changes we were making were well received (or at least neutrally received) by the important stakeholders. One major risk was the de-emphasis of cost reduction as a key metric for the project. The decision was made by the team to focus on lead time in order to raise on-time delivery and quality. This should indirectly lead to lower costs, but there was no concerted effort to cut direct costs. The de-emphasis on cost reduction was not really an issue by the end of the internship because of the success the team had in achieving its other goals.

One additional comment on the idea of influence without authority at Glenrothes must be discussed before moving on to the next section. Anyone who held the respect of others and strongly voiced his or her ideas could get a lot of things done at Raytheon Glenrothes. Even though it was a functional structure, most people were willing to help someone with strong ideas.

8.3. Cultural Lens

8.3.1. Symbolic Meaning of the Project

The project had two major significant symbolic meanings for the employees at Glenrothes. The first was the indoctrination in the Raytheon way of doing things. Raytheon was making a push to create a "one RSL" mindset across the Raytheon UK locations, and this was one of the attempts to do this. Lean and Six Sigma were tools that RSL was using across the different locations to generate improved performance, and this project was the main Lean Six Sigma effort at Glenrothes.

The second was a symbol of change and new ideas. By bringing an LFM intern onto the project with so much responsibility, a message was sent to the circuit card department that management was serious about making changes and finding new ways of being successful.

8.3.2. Cultural Change within Circuit Card Assembly

One lasting change this project will have on the team members and others in circuit card production is that cookbook solutions are no substitutes for studying the problem and trying solutions that fit with the environment. This sentiment may not reach the other product lines at Glenrothes, but at least a few members of the team saw how powerful new ideas tailored to the specific problem could be.

The culture on the factory floor also changed from the beginning to the end of the internship. After circuit card production was divided into three teams of product-focused cells and daily meetings were implemented, small changes were observable out on the floor. Operators in different parts of assembly had a forum to start communicating. Engineers and other support people started communicating directly to operators instead of through supervisors when there were problems. The operators, leads, and supervisors could see the results of their cell more clearly and started seeing the light at the end of the tunnel.

By the end of the internship, all the metrics of manufacturing performance were strong or improving. It takes a long time to change attitudes and culture, but at least circuit card assembly is headed in the right direction.

8.3.3. Cultural Differences Between Scotland and America

A discussion on culture is not complete without exploring the differences between working in Scotland versus the United States. The first unique aspect of the Scottish culture is the homogonous nature of the workforce. They were almost all native Scots, with a few English and even fewer Americans. This is actually not that different than a plant the author once worked at in a small town in Minnesota. Although this homogeneity was an interesting feature, it did not cause any problems except when they had to deal with international customers. The language was different enough that communication between the Raytheon Scots and American customers was not always smooth. To have an American there who was able to put things in terms the US customers could understand and not have to worry about slowing down and repeating things was beneficial.

The next cultural difference was their more traditional gender roles. Nearly all engineers and managers were men, while most of the operators were women. The operators were often referred to as "the girls". Because this was the culture they had all grown up with, this forced an adjustment for the author to fit in while trying to avoid gender stereotypes.

The other cultural difference was in the personality of most of plant personnel. They were reticent in groups and good-natured. They avoided conflict and preferred to avoid making waves. When the manufacturing manager would hold a plant-wide briefing, he would rarely receive any questions from the group. This actually is not that different than the author's natural personality, so he fit in well at Glenrothes.

The ease in which the author was able to assimilate quickly probably owes somewhat to his Minnesota heritage. There is actually a stronger cultural difference between Boston, Los Angeles, and Minnesota than between Scotland and Minnesota. Also, the fact that the language was similar made the transition fairly easy and the other cultural differences manageable.

9. Conclusion and Recommendations

9.1. Summary of Analysis

Manufacturing Metrics

Both Lean Manufacturing and Quick Response Manufacturing suggest focusing on a single metric to drive improvement in the factory. Lean uses the idea of waste, while QRM favors lead time. Because circuit card assembly in Glenrothes does not fit neatly on the Lean or QRM end of the Key Production System Characteristics Continuum, neither metric is obviously the right choice. The improvement team initially focused on waste and generated some improvement. Midway through the project, lead time was raised to the most important metric, and after that lead time improved to less than 2 weeks in the assembly part of the process. Improvements in on time delivery, customer satisfaction, and quality followed. In this particular mixed system characteristic environment, a focus on lead time was a clearer rallying point than waste and led to significant improvement.

Factory Organization

Both Lean and QRM recommend segregating production by families, with QRM allowing for a more liberal definition of product family. Lean and QRM are also not that far off in how they recommend organizing production. They both prefer a cellular approach, with Lean including flow lines as an option. As with product families, the QRM cell is much less restrictive and can be setup up in far more environments than can a Lean cell. Once the right families have been selected and cells organized, then the major benefits of both Lean and QRM can be realized – the employee involvement and ownership that results from owning what goes on in the cell. If the tight restrictions of Lean flow do not fit the production environment (the mix is too high or products are too customized), then we are left without a solution using only the Lean toolbox. But if we turn to QRM in this case, hope is not lost and we can still organize into loose product families and cells. We can then reap the benefits of improved operator ownership.

Lot Sizing Decisions

Lot sizing decisions are much more complicated than just an EOQ formula or a drive toward lot size of one. In an environment with a high mix of products, lot size decisions are very complicated and require the consideration of numerous factors. In Glenrothes, lot sizes were chosen at the start of the internship with a very rough heuristic. These actually turned out to be reasonably effective at providing short lead times without incurring excessive setups and reaching capacity limits.

The most important aspect of lot sizes from an improvement perspective is the need to cut setup times, which is part of both Lean and QRM philosophy. The benefits of setup time reduction is not limited to a particular environment with certain production system characteristics.

Production Control Strategy

Here too we see that one particular production control strategy does not fit all production environments. A Kanban system for every process is not the best form of production control in environments that have higher mix, lower volume, fluctuating demand, and a higher degree of customization. The production control strategy must be tailored to fit the environment, which is illustrated by the case of circuit cards in Glenrothes. By the end of the internship, circuit card assembly was operating on a pull system between cells with a visually-controlled push system within cells. This was working very well even though all steps were not pulled by the customer as proscribed by Lean thinkers. Some improvement is still possible for Glenothes CCA by investigating a CONWIP system or form of DBR within the cells.

Material Presentation to the Line

Although not always a critical issue for improvement, how material is presented to the line does impact a manufacturing system's performance. The choices for the material presentation strategy include point of use, central stockroom, kitting, or some combination of these three. Lean advocates point of use and sees any form of central stockroom or kitting as waste. QRM does not weigh in on the issue. Other factors besides the four Key Production System Characteristics come into play when creating a material presentation strategy. These include quantity, size, value, and commonality of parts.

For Glenrothes manual assembly, the best form of material presentation was a combination of point of use and kitting called "Kitting After Point Of Use". Parts were stored at point of use with no duplication of part locations for different board types. Operators were required to bring the right parts together from this point of use location and bring this "kit" to their workstation. Most of the waste present at the beginning of the internship in the form of operators searching for the right parts and missing parts was eliminated with this new material presentation strategy.

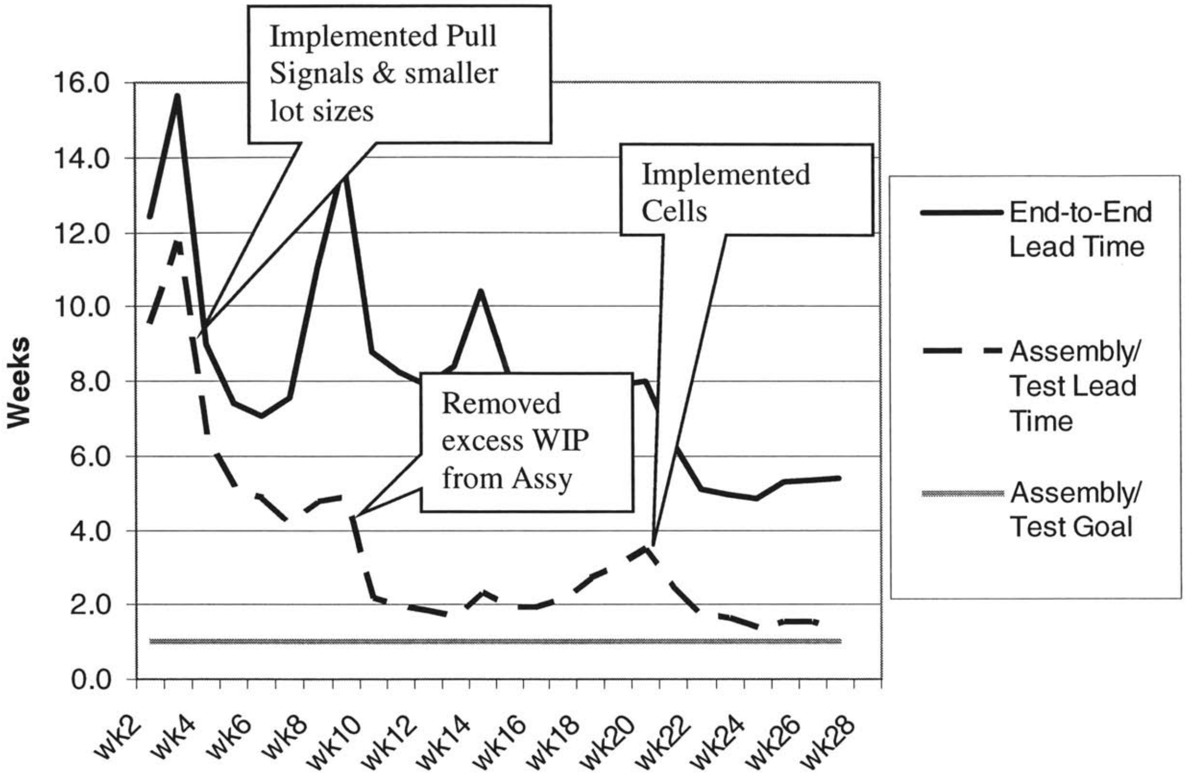
9.2. Internship Accomplishments

Chapters 3 through 7 contain a great deal of detail regarding changes made to the CCA production system in Glenrothes, but little data to back up the claims of improvement. This section captures the main areas of performance improvement (lead time, inventory, on-time delivery, and customer satisfaction) and ties the numerous changes made into these improvements.

Lead Time

Figure 12 shows the lead time progress made during the course of the internship for Family B. Two lead times are plotted, one for the end-to-end process, and another for just the assembly/test cell. Because inventory of each circuit card was held in the buffer between the machine cell and assembly/test cell, the lead time for the assembly/test cell is also the lead time from receipt of customer order to delivery.

Figure 12: Family B Lead Time Progress



The graph indicates significant progress was made in reducing assembly/test lead times in the first half of the internship, when Lean was the primary philosophy driving the team's actions. Around Week 4, the modified pull system was implemented and lot sizes were changed. Both of these were positive steps and reduced lead time from 10-12 weeks down to 5 weeks. Then WIP that did not have an associated order for that month was removed from the line and placed in the buffer between the machines and assembly/test. An interesting note about these two improvements is that lead time was not being measured at the time, so the team did not even know how much impact they were really making.

However, these two improvements were temporary. The cells had not been formed yet and there was no good method to manage inventories in the assembly/test or machine portions of the process. Assembly/test lead time began creeping up through Week 21, at which time cells were implemented. Lead time was being measured at this time, so it was easy to see week-by-week progress.

Along with the cells came the implementation of visually-controlled push using the inventory control board and daily production targets. The board was a great tool for the lead and supervisor to manage workflow and resources, while the daily targets were a great motivator for the production team. Soon after cells were implemented, the slide in assembly/test lead time was reversed and a new low for lead time of close to one week was reached near the end of the internship in Week 28.

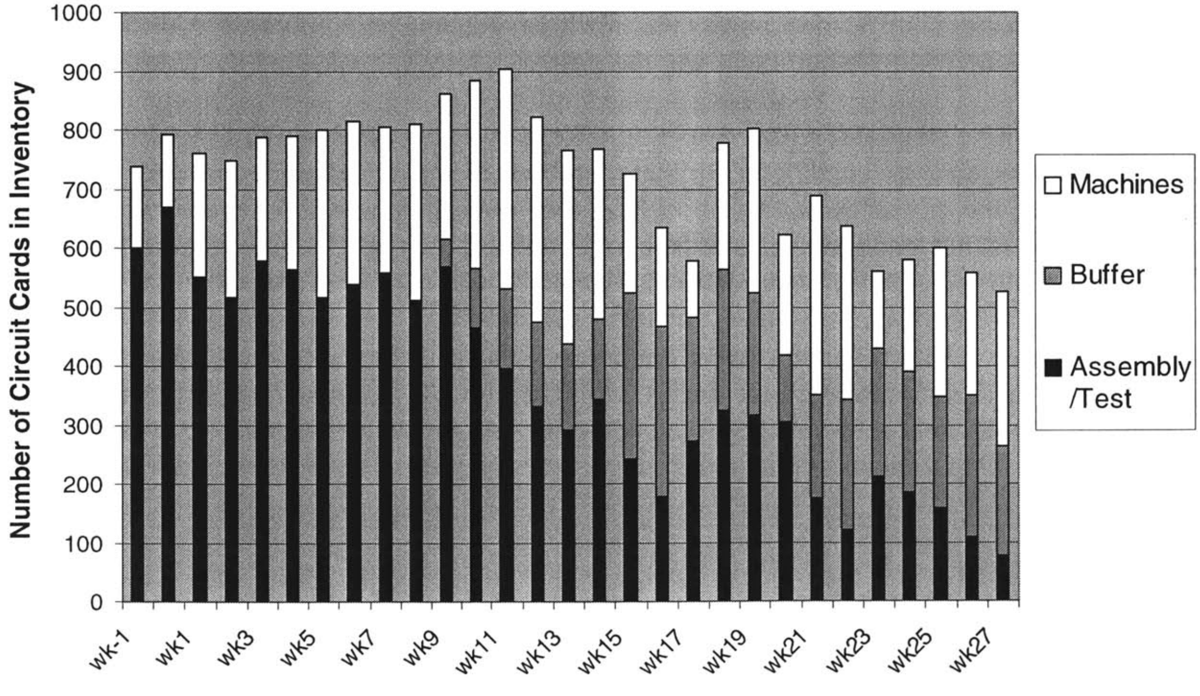
The end-to-end cycle time was also reduced significantly, from 12-15 weeks down to 5 weeks. Most of this improvement occurred as a result of the reduction in assembly/test lead time. This is understandable since much less attention was paid by the team to the machine cell. Also, an inventory level of about two weeks was chosen to be held in the buffer between the machine cell and assembly/test cell, so this automatically adds two weeks to the overall lead time. The machine cell and buffer are the next greatest areas for lead time improvement within Glenrothes CCA with assembly/test lead time performing very well at one week.

Inventory

Overall work-in-process inventory was reduced by 30% over the course of the internship (from 800 to 550 circuit cards). WIP inventory in assembly (including buffer), where most of the team's effort was focused, dropped by 50% (from 600 to 260 circuits cards). It is also important to note that the inventory held in the buffer does not add to the chaos of the system, whereas the inventory within the assembly and machine cells does increase chaos. The amount of "uncontrolled" inventory (WIP not including buffer) went from 800 to 320 circuit cards, a 60% decrease.

The inventory trend looks very similar to the lead time trend, which is not surprising. Application of Little's Law tells us that if throughput remains constant, inventory will be directly proportional to lead time. Throughput varied somewhat over the course of the internship, but the relationship between inventory and lead time is still very apparent.

Figure 13: Family B Work-In-Process Inventory

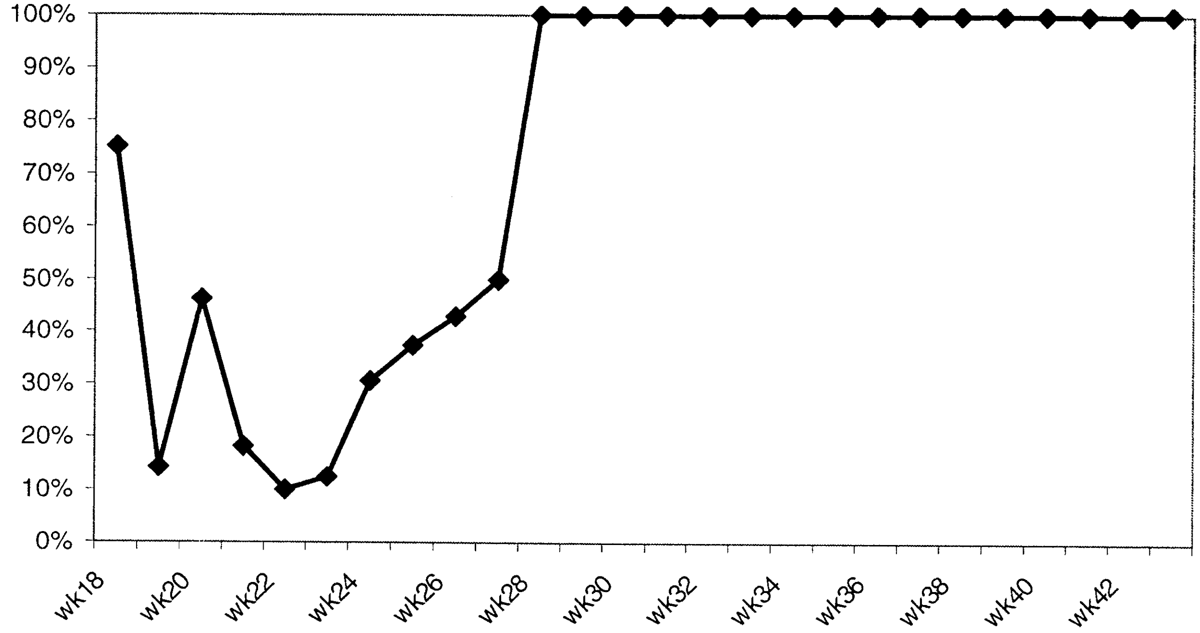


Inventory can almost be equated with lead time, where 100 boards of inventory equals one week of lead time. The black bars show the reduction of inventory in assembly/test, which corresponds to the major reduction in assembly/test lead time. The diagonally-lined bars show the growth (and leveling off) in the buffer between the machine cell and assembly/test cell. The white bars show the inventory in the machine cell, which remains relatively constant. This is not surprising since this area was not a focus of improvement efforts.

On-Time Delivery

Figure 14 contains on-time delivery data from about 4 months into the internship through 3 months beyond the end of the internship. Data from the first four months of the internship (Weeks 1-17) is omitted because on-time delivery was measured differently up until that time.

Figure 14: On-Time Delivery



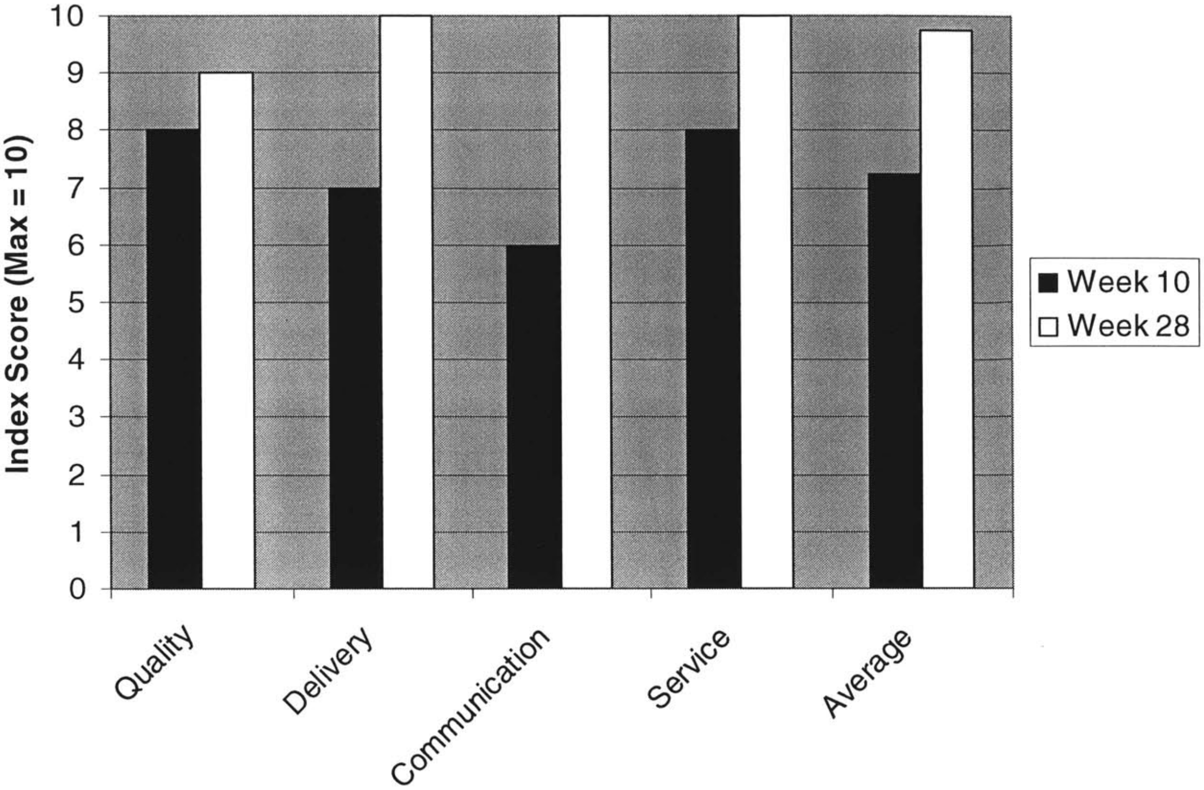
A dramatic improvement occurred between Week 28 and Week 29. As lead time dropped below 2 weeks for a number of weeks prior to Week 28, on-time delivery began a turnaround and reached 100% by Week 28.

Because the gains in lead time were sustained after Week 28, on-time delivery remained at 100% through Week 43. This is a significant achievement considering so many other improvement efforts within circuit card assembly at Glenrothes have tended to revert back to the old way of doing things.

Customer Satisfaction

Customer Satisfaction also showed significant improvement over the final three months of the internship as shown by Figure 15.

Figure 15: Customer Satisfaction Index



The Customer Satisfaction Index is derived from discussions with the customer on the topics of quality, delivery, communication, and service. All indices improved (with all but one reaching a perfect 10) by the end of the internship, indicating that the improvement efforts were creating value for the customer.

9.3. Thesis Assumptions/Application Recommendations

The analysis performed in this thesis assumes a fixed production system, meaning that the mix, volume, demand variability, and degree of customization are all fixed along the Continuum. Any factory is easier to manage and fits better with Lean principles if mix can be reduced, volume increased, demand variability reduced, and degree of customization lowered. The first step in any improvement effort should be to look at where the existing production system falls on each of these dimensions and see if any or all can be moved to the left on the Continuum without upsetting customers.

For example, demand variability may be artificially induced by the bullwhip effect, and actual demand from the end customer might be rather smooth. In this case, one should work with the immediate customer to understand why he is sending demand signals to you that differ in variability from the end customer's demands. A reasonable explanation for this is that the immediate customer might be producing in large batches, so one option is to work with this customer to setup a steadier product demand. In a high mix situation, one alternative is to rationalize this mix and get to a lower mix state. On degree of customization, subsystems or modules could be created that include most of the possible options from the customer so that each order is not a custom one.

If these types of changes are possible to the system, then one may be able to move towards the Lean end of the Continuum, where all the Lean principles can be applied with success. Only when this is not possible, or when customers value a system that can operate towards the right on the Continuum, does QRM enter into the picture as the best alternative to Lean.

Another assumption made in this thesis is that all products in the production system have a certain set of characteristics, and that there are no subgroups of products that have different characteristics. After trying to move to the left on the Continuum, the next step is to try to find product families that may suit either Lean or QRM very well. An initial analysis may have shown the system to have "mixed" system characteristics like Glenrothes CCA, but underlying this may be two systems that are at opposite ends of the Continuum.

A good example of this is some new circuit card products that are planned for Glenrothes. One in particular has a demand of 3,000 a month, which is much higher than any other circuit card currently assembled. Instead of trying to fit this into the current manufacturing system designed for high mix and low volume, attempts should be made first to find ways to set up dedicated equipment and cells for this one product. This may not be possible on the SMT or automated thru-hole machines, but the rest of assembly and test could have a dedicated cell. This cell could then be designed based on lean principles – single-piece flow, Kanban production control, etc.

Another example comes from a common feature found in many companies often called the 80/20 rule – 80% of the volume comes from 20% of the products. If that 80% fits the four characteristics suited to a Lean production system, then Lean can be the method of improvement for that 80%. The 20% may be well-suited to QRM methods, so a separate production system can be setup on these principles.

Many managers do not want to hear the message that different principles must be applied to systems with different characteristics, because this means that there is not one overarching method they can apply to all manufacturing systems. They have tried to do it with Lean, but it simply does not fit everywhere. There is no substitute for thorough analysis of the actual system followed by the implementation of the right driving metric, factory organization, lot sizes, and production control strategy that fits the environment. One is lucky if these happen to be aligned well with Lean or QRM. For those environments that are not so well aligned to one end of the Continuum, this thesis provides guidelines for how to think about manufacturing improvement. In the end, there is no one-size-fits-all manufacturing philosophy.

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