Teaching Lean (Manufacturing) in Operations Management [004-0634]

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Abstract

"The Toyota Motor Company has risen to a place of world prominence in the automotive industry by redesigning the mass production system into the Toyota Production System (TPS)". Clearly the TPS is one of the most extraordinary innovations in the history of manufacturing and under a variety of labels (JIT, World Class, Lean) has been widely copies throughout the world. However many OM courses and textbooks give very little attention to lean manufacturing systems and cell design. Participants in this session will receive a three lecture set of notes dealing with factory designs in general, lean factory designs in particular and implementation strategies for converting a mass production factory into a lean production factory: Part I: The evolution of factory design and the development and propagation of the Toyota Production System; Part II: Factory design for lean: linked-cell manufacturing systems; and Part III: A step-by-step methodology for converting the mass system into the lean system. The author will also discuss Six Sigma and its relationship to lean manufacturing.

Introduction

When the Toyota Motor Company redesigned the mass production system, they changed the final assembly lines into a mixed model final assembly line to level the demand on their suppliers. They converted the linear subassembly lines into U-shaped subassembly cells and they redesigned the job shop into manufacturing cells. Final assembly operates with a takt time, and the cells are balanced to produce the daily demand. The system is designed to operate on a "make one, check one and move one on" (MO-CO-MOO) basis.

The design of a lean manufacturing system can be based on axiomatic design rules. These rules are operationally true but you cannot derive them – you just evolve them out of the practice – i.e., how the system works.

The first rule is applied to the factory. The final assembly line (FA) has a takt time that is based on the daily demand for the goods being made in the factory. The daily demand is based on the monthly demand which is based on the annual demand. The leveled daily demand is what permits all the part-producing elements to be balanced – to produce the same AMOUNT every day in whatever mix the downstream customer requires. This is an easy rule to write but it requires lots of engineering to execute. Final assembly has to be converted to a mixed model final assembly that makes any of the goods in any order. The inverse of the takt time (takt time is really just the cycle time for final assembly) is the production rate for final assembly. Knowing the takt time sets the pulse or production rate for the factory. Making it mixed-model provides a leveled or smoothed demand for goods for the rest of the factory and all of the supply chain.

The second rule is that all the goods producing aspects of the system operate on a MO-CO-MOO basis. This is also called one-piece flow. The final assembly, all the subassemblies and all the component part manufacturing is performed on a Make One – Check One – Move One On basis. Final assembly is already doing this. The subassembly and component part manufacturing factories must be redesigned into U-shaped manufacturing and assembly cells to achieve one-piece flow.

The design of the manufacturing and assembly cells is based on a design rule wherein the machining time for any part in any machine in the cell is less than the necessary cycle time (NCT). The NCT is based on the takt time, being slightly less to provide a margin of safety for the suppliers to final assembly.

The third design rule covers the production and inventory control system, a pull system known as KANBAN. The manufacturing components are connected to final assembly with kanban links which withdraw material from the subassembly and component suppliers as needed by final assembly and give production orders to all the suppliers automatically. This rule governs the maximum inventory in any link. The maximum inventory is equal to the DD times the lead time plus a safety stock. So lead time accounts for all the transportation time, delay time, processing time etc. in the links connecting the subassemblies and component manufacturing to final assembly.

Using these design rules, a linked-cell manufacturing system can be designed. Naturally it still must be operated by people using automation where it makes sense to meet the quality (perfect) and quantity (don't overproduce) needs of the system. The result of these system design rules is a robust system that is simple to operate – therefore everyone who works in the system understands how the system works – but can made low-cost, superior quality complex products with the minimum of daily information.

HOW MANUFACTURING SYSTEM DESIGNS EVOLVE

The linked-cell manufacturing system (L-CMS) design also known as, the lean shop, is an outgrowth of the previous two manufacturing system designs, the job shop and the flow shop. The job shop as a manufacturing system design evolved during the 1800s.These early factories replaced craft or cottage manufacturing when it became necessary to have powered machines. A functional design evolved because of the *method* needed to drive or power the machines. That is, water power. The job shop design became known to the historians as the American Armory System. People from all over the world came to New England to see this system, and it was duplicated around the industrial world.

In the early 1900s, the first vestiges of the flow shop began to emerge. Flow line manufacturing began for small items and culminated with the moving assembly line at the Ford Motor Company. Just as in the 1800s, the world again came to see how this system worked, and this new design methodology was spread around the world. Over time a hybrid system— a mixture of job shop and flow shop—evolved. This physical design permitted companies to manufacture large volumes of identical products at low unit costs. This design became known as mass production, see **Figure 1**.The job shop produced components in large lot sizes according to the economic order quantity strategies. The subassemblies lines feed components to storage systems and to final assembly. This system produced the goods that helped America win WWII and become a world leader in manufacturing. The physical design was the result of achieving certain function requirements like low cost.

THE TOYOTA PRODUCTION SYSTEM (TPS)

After WWII, the Toyota Motor Company, led by the genius of a manufacturing engineer named Taiichi Ohno, developed a new manufacturing system design known initially as the Toyota Production System (TPS) and later the just-in-time/total quality control (JIT/TQC) system or world class manufacturing (WCM) system. In 1990, it was **finally** given a name that would become universal, *lean production*. What was different about this system compared to mass production? **It's design!**

First, in lean production, final assembly is converted to mixed model so that the demand for subassemblies and components from the suppliers is the same every day. This is called leveling or smoothing production. Second, the subassembly lines are converted into U-shaped to cells, often eliminating conveyor lines. Third, the job shop is converted to U-shaped cells. The cells operate on a one-piece flow basis like final assembly. The *subassembly* and *manufacturing cells are linked* to final assembly by kanban to form an integrated inventory and production control system. The result is low-cost (high-efficiency), superior quality (no defects), and on-time delivery of unique products from a flexible system. The new design operates in ways the old "mass production" system could not. The final assembly lines were designed (flexibly) to handle mixes of models so that quantity of all the components pulled into the final product was the same day after day. The cells are designed to handle changes in volume, mix and changes in design.

When we say the lean shop is flexible, we mean the system can readily adapt to changes in customer demand (volume and mix) and changes in product design (new products or changes to the existing product). In the lean cells this means that setup times have been greatly reduced.

The lean shop has integrated control functions which means that the system level control functions (for quality control, inventory control, production control, and machine tool reliability) are designed into (integrated) the manufacturing system. This functional integration is quite different from getting the computer-aided design (CAD) computer to talk to the computer-aided manufacturing (CAM) computer. Because the new method is based on a different manufacturing system design rather than expensive computer technology, it requires less capital investment.

The lean shop is designed to produce superior quality products. Toyota believed in total quality control and taught it to everyone, from the company president down to every production worker. They were able to change from a country that made junk to a nation that could give customers products of high reliability. This was accomplished through a redesign of the manufacturing system into a single-piece flow methodology where every part and every assembly is checked after each processing step.

The reduction of variation is the key to continuous improvement. The kinds of variation we need to consider are:

- Variation in quality (defects/million)
- Variation in process time (hrs/part)
- Variation in output (parts/day)
- Variation in cost ($/part)

These kinds of variation are reduced through the implementation of lean manufacturing and the continuous changing (redesign) of the MSD.

The system is designed for efficiency. The elimination of waste through the efficient use of space, people, machine tools, and the material handling and storage elements are what make this system lean.

The system is designed for uniqueness and creativity on the part of engineers and workers to develop and improve processes, reduce equipment failures, reduce changeover/setup times and continuously improve the design of the workplace (methods improvement).

More significantly, the placement of the processes in the manufacturing and assembly cells requires unique processing solutions to bring the processing times well under the takt time. While many of these processes are well guarded company secrets, some examples will be given in the section on lean cell design.

MANAGEMENT PHILOSOPHY MUST CHANGE

Redesigning the manufacturing and production system requires a change of philosophy within the company. Employee involvement and teamwork are rooted in the idea that no one employee is better than another. Everyone is an associate. There are no private offices. There is no executive lunchroom. There are no preferred parking places (except for the associate of the month). The system in which management tells workers what to do and how to do it must be changed. However, this change requires that the CEO have the courage to shift some of the decision-making power from management to the people on the factory floor. Restructuring the manufacturing system and the production system helps this most difficult transition. The biggest change is psychological—convincing the workers on the factory floor that nothing is more important than what they think and how they feel about the manufacturing system. For this change to work, the operators must have input to the new manufacturing system design. The way the work is done must be clearly defined by the workers. It must be their "cell design." Their achievements must be tracked closely and recognized. People are not going to "bust their guts" unless there is a strong reward system.

Toyota developed a new and different manufacturing system that was flexible, delivered quality products on time at the lowest possible cost, and did so day after day. They educated their work force and placed their best engineering talent on the production floor rather than in the design room. Those who say that the Japanese are not inventive or ingenious have simply looked in the wrong places for evidence. However, much of the unique processing technology was hidden in the manufacturing cells held by the sole-source vendors and suppliers to the main plant (the final assembly plant). This is one of the reasons why lean manufacturers use sole or single source suppliers. The proprietary process technology is captured and held in one place. It is difficult for those outside the company to get access to the proprietary process technology.

PRELIMINARY STEPS TO LEAN PRODUCTION

Integration of the production system functions into the manufacturing system requires commitment from top-level management and communication with everyone, particularly manufacturing. Total employee (and union) involvement is absolutely necessary, but it is not usually the union leadership or the production workers who raise barriers to lean production. Those in middle management have the most to lose in systems-level changes as their job functions get integrated into the manufacturing system.

The preliminary steps are as follows:

1. All levels in the plant, from the production workers (the internal customer) to the president, must be educated in lean production philosophy and concepts and understand how lean is different from mass. Physical simulation of cells versus job shops is very helpful in accomplishing this step.
2. Top down commitment and involvement is critical. The entire company must be involved in the journey. The top people must be totally committed to the change, set an example, and be active leaders and, in fact, system designers.
3. Top management must understand that lean design will lead to financial decisions that are opposite to current management accounting practices that have led to mass production in their company.
4. The selection of measurable parameters that will track the change is critical. Everyone in the plant must understand that cost, not price, determines profits. Everyone must be committed to the elimination of waste as these steps are put in place.
5. Encourage your internal customer to set tough goals, realistic measures, and even timelines. Let them know who is the best in the class by using benchmarking.
6. Education and training of the operators is vital. Operators must understand why change is necessary and how to change. The operators must be empowered to design the cell, and then to implement the quality control, machine tool maintenance, production control, inventory control, process improvements, and setup time reduction and then to make process/cell improvements later.

7. The company must spread the success and reward the teams. The company must share the gains with those who contributed. Many companies feel that bonus payments are the way to go to reward people.
8. The reward structure of middle management must be changed to support the system design.

LEAN PRODUCTION METHODOLOGY FOR IMPLEMENTATION

The basic implementation strategy outlined here is the amalgamation of the methods used by many companies to successfully implement lean manufacturing. These companies were not suppliers to Toyota and not privy to the Toyota Supplier System training and philosophy.

- Design the L-CMS for flexibility
  - Mixed-model final assembly
  - Subassembly cells
  - Manufacturing cells
  - Fast changeovers everywhere
- Integrate the critical control functions.
  - Quality control (perfect quality through defect prevention).
  - Machine tool/equipment control/reliability with no breakdowns.
  - Production control (right time, right quantity, right place).
  - Inventory control (minimize).
- Autonomation
  - Autonomous control (computers, automation, robotics) of quality and quantity in the cells and systems.
- Design the enterprise around the L-CMS.

This design strategy is broken down into critical steps in **Table 1**. Notice that *autonomation*, part of lean cell design, the autonomous control of quality and quantity, comes very late in the methodology, after functional integration has been achieved. That is, the system must be redesigned, simplified, and integrated before computers and automation are applied as part of concurrent engineering becomes the last step as part of an effort to restructure the rest of the enterprise, improving the cell designs, taking them from interim cells (using single cycle automatics) to lean cells (using machine tools and processes designed for single-piece flow).

This approach implements a manufacturing system design that permits rapid deployment of new products and rapid production of existing products, as well as accommodating changes in the product demand, so it is the winner when it comes to time-based competition. Companies that employ this strategy become the factories with a future because the manufacturing system is simplified before computer technology is applied. This approach avoids large financial risks, and makes the implementation of automation easier.

The order of the design steps outlined in **Table 1** is important. Many companies have implemented kanban and made significant reductions in inventory levels before the necessary system and cell design steps were implemented. Such implementations often result in failure. Even worse, many companies have tried to implement costly computer integrated and MRP strategies without first implementing lean production resulting in computerization of an inefficient manufacturing system.

If you become a supplier for Toyota, they will teach you steps 2 through 7 and your company will become the sole source for this component or subassembly. However, you are free to use this methodology to supply similar components to other companies.

After completion of the steps, your company will have a new look on the factory floor. If you took a picture from high above, it might look like **Figure 2**, kind of jumbled in some areas as the cells are arranged for good part movement and access by operators who may be working in more than one cell. Overall, it is a simple linked-cell system capable of making complex products – a system that everyone who works in the system understands how the system works or operates. Can you say that about your manufacturing system? Do you know how your MRP computer software keeps track of inventory and makes sure nobody runs out of supplies? Here is some detail on the steps lean – Black's Blueprint to MO-CO-MOO.

TABLE 1 Lean Production Methodology for Implementation		
1	*Level and balance the manufacturing system, smoothing the material flow* (Monden 1983): Leveling involves the development of mixed model final assembly. Level or smooth the demand on the cells or the suppliers. Balancing is getting the output from the cells to match the needs of final assembly.	● Establish the daily demand ● Develop mixed model final assembly; takt time ● Balance the output from the suppliers ● Develop single-piece flow in subassemblies ● Sequence subassemblies with order of assembly
2	*Design or reconfigure the manufacturing system*: Design and implement manufacturing and assembly cells. The design of the manufacturing system must consider the design of the product and the need of the internal and external customers while meeting the FRs for system stability. FRs functional requirements.	● Standard work for operators in cells ● Design/implement manufacturing cells
3	*Setup reduction, changing methods and designs to reduce setup time* (Shingo 1985): Setup time is delay time. Affects lot size. Optimum lot size is one. Use SMED because it involves everyone on the factory floor (SMED = single minute exchange of dies). Permits small lots and creates flexibility.	● Teach everyone SMED ● Develop one touch setups in the cells ● Operators perform changeovers
4	*Integrate quality control into the manufacturing system* (Shingo 1986): Does the manufacturing process satisfy the design specifications every time? Inspection to prevent the defect from occurring (pokayokes).	● Inspect to prevent defects ● Use the seven (7) tools for quality control and line stop ● Teach everyone quality ● Zero defects
5	*Integrate preventive maintenance* (Nakajima 1988): Do the machines and people behave reliably? Design equipment to be reliable. Design methods to check people and methods for people to check machines, identify and solve problems. System will breakdown if machines and support equipment fail.	● Machines designed for reliability using TPM ● Operators solve problems ● Operators perform daily maintenance
6	*Integrate production control, link the cells, pull material to final assembly*: Control the where, when, and how much material. The design of the manufacturing system defines flow and the kanban operates within the structure. This is integrated production control or kanban (Black 1991).	● Link the cells ● Pull material to final assembly ● Kanban drives the production
7	*Integrated inventory control*: Reduce the WIP in the links that connect the cells. This is control of the quantity of material in the links. Minimized and optimized and controlled by the internal customers, the users of the materials (Black 1991).	● Gradually remove inventory from links ● Expose problems ● Solve problem, improve system TPT
8	*Integrate the suppliers: make them JIT manufacturers just like you*: Suppliers become remote cells. Suppliers become partners. Relationship built on trust. This is how real technology transfer takes place.	● Suppliers are sole source ● Teach suppliers steps 1 thru 7
9	*Autonomation: autonomous control of quality and quantity within the manufacturing system*: Automate the integrated pull manufacturing system.	● Design/implement lean manufacturing cells ● Apply computers, robots, automation
10	*Design the lean enterprise around the L-CMS.*	● *Design new products concurrently with customers in mind* (Whitney 1992). ● Design/implement lean manufacturing with lean machine tools.
TPM = Total Productive Maintenance TPT = throughput time SPF = Single piece flow		

STEP 1: LEVELING, BALANCING, SEQUENCING, AND SYNCHRONIZING THE MANUFACTURING SYSTEM

The lean production system depends upon *smoothing the manufacturing system.* In order to eliminate variation or fluctuation in quantities in feeder processes, it is necessary to eliminate fluctuation in final assembly. This is also called *leveling* the final assembly. It means the demand for the subassemblies and components from the suppliers is leveled. Here is a single example to show the basic idea. First, we need to calculate the production rate and its reciprocal or cycle time which is based on the daily demand.

$$\text{DD} = \text{average daily demand for parts} = \frac{\text{monthly demand (forecast plus customer orders)}}{\text{number of days in each month}}$$

$$\text{TT} = \frac{\text{available hours / shift}}{\text{average DD / shift}} = \text{takt time for final assembly}$$

$$\text{TT} = 1/\text{production rate for final assembly (FA)}$$

$$\text{PR} = \frac{\text{average daily demand (parts)/shift}}{\text{available hours/shift}} = \frac{\text{DD}}{\text{hrs/day}} = \frac{\text{parts}}{\text{minute}}$$

But in reality *CT = TT (1 – Allowance).*

This incredibly simple design rule highlights the way in which lean companies calculate takt time for FA and cycle time for cells and processes. Life is simpler when the mass production system has been eliminated and a linked-cell system has been installed.

Here is an example of how cycle time is determined for a mix of cars at final assembly. Suppose that the forecast is for the assembly of 240 cars per day and 480 production minutes are available (60 minutes x 8 hours per day). Thus, the cycle time is equal to 2 minutes. Cycle time is called the takt time in this case. Every 2 minutes a car rolls off the line. Suppose that the mix is as given in **Table 2**.The sequencing of the four types (models) of cars going down the assembly is shown in the sequence. The subprocesses that feed the two-door fastback are controlled by the cycle time for this model. Every 4.8 minutes, the rear deck line will produce a rear hatch for the fastback version. Every 4.8 minutes, two doors for the fastback are assembled in synch with the final assembly line. The doors are mounted on the body, initially painted with the body, then removed when the car exits painting, placed on an overhead conveyor which transports the doors to the door line which has the same mix of product and cycle time as the main assembly line. The doors are trimmed (i.e., filled with windows, door handles, etc.) in sequence and in synch with final assembly. If the final assembly line stops, so does the door line. Other subassemblies, like the seat assembly lines and other main subassembly lines for parts which are special to the car model are done this way**.** After trimming, the door is then returned to the line and goes back on the same car body from which it was earlier removed. This is an example of *synchronizing* or *producing in sequence*.

TABLE 2 Example of Mixed Model Final Assembly Line That Determines the Cycle Time for Model

Q	Car Mix for Line Model	Cycle Time by Model (min)	Production Minutes by Model	Sequence (24 cars)
50	Two-door coupe	9.6	100	TDC,TDF,TDF, FDS, FDW
100	Two-door fastback	4.8	200	TDC,TDF,TDF, FDW, FDW
25	Four-door sedan	18.2	50	TDC,TDF,TDF,TDS,TDW
65	Four-door wagon	7.7	130	TDC,TDF,TDF, FDW
	240 hr cars/ 8 hr		Takt time = 480 min/240 = 2 min per car	

Most components are simple *sequenced* to the line. For example, every car, regardless of model type, has an engine. Engines for this assembly line are produced at a rate of one every 2 minutes. Each engine needs four pistons. Therefore every 2.0 minutes, four pistons are produced. Parts and assemblies are produced in their minimum lot sizes and delivered to the next process, under the control of kanban. Engines are often made elsewhere, shipped to the assembly plant and put in the right *sequence* for the cars coming down the line.

Balancing is making the output from the cells equal to necessary (or daily) demand for the parts downstream. Many parts or components are not made in synch with final assembly, only the daily quantity is the same. In summary, small lot sizes, made possible by setup reduction within the cells, single-unit conveyance within the cells, and standardized cycle times are the keys to having a leveled manufacturing system. Over time, one strives to make the cycle time in the cells equal to the takt time for final assembly but at the outset, matching the daily demand is sufficient. Ultimately, every part, sequence of assembly operations, or subassembly has the same number of specified minutes as the final assembly line.

For example, when the car body exits from painting, an electronic order for the seats is issued to the seat suppliers. The seats are made in another nearby plant in the same order as the cars on the assembly line. They are made and delivered in the same amount of time as it takes the car to get from the paint area to the station on the line where seats are installed. That is, seat manufacturing is *synchronized*. The minimum number of workers needed to produce one unit of output in the necessary cycle time is used. The lean shop is a *balanced and synchronized* manufacturing system. Actually, a synchronized system is the ultimate leveled system. The run size is one unit in final assembly. Many subassemblies are shipped to final assembly in lots or batches and put on the line at the same takt time. These items are put in the correct sequence so they get to the right car at the right time. This is called *sequencing*. The dashboard subassembly may be done in this way or it may be done in a synchronized fashion if paint matching is a problem.

Subassembly Cells

At the same time that the final assembly area is being designed, the subassembly (flow) lines (that use conveyors) are reconfigures into U-shaped cells, see **Figure 3**, to make these systems operate on a single-piece flow basis. The operations in an assembly cell are usually all manual so the operator must stay at a station until the task is completed, but the operators can move from station to station to perform multiple operations. Of course, the long setup times typical in many flow lines must be vigorously attacked and reduced so that the cell can be changed over quickly from one product to making another. This makes them flexible and compatible with the cells designed to make piece parts and with the other subassembly lines and final assembly lines. Again the cells are designed to manufacture specific groups or families of parts. In the U-shaped layout in **Figure 3** workers 2, 3, and 4 cover multiple operations. Notice that workers 3 and 4 share operation 7. Workers 1 and 5, are covering operations 1, 11, and 12 using a rabbit chase (workers follow each other around the loop). The need to line balance (make task times equal) the flow line has been eliminated. This is accomplished by using standing, walking workers who are capable of performing multiple operations. For the cell, the cycle time is 0.43 minute (to produce 1056 units per shift) which is 26 seconds per part. The cell must produce four parts every 2 minutes to match the demand at final assembly (each product needs four of these motors).

STEP 2: RESTRUCTURE THE JOB SHOP

In the L-CMS, cells replace the job shop. Restructuring the job shop is critical to reorganizing the basic manufacturing system into manufacturing cells that fabricate families of parts. This prepares the way for systematically creating a linked-cell system for one-piece movement of parts within cells and for small-lot movement between cells. Creating cells that can produce to the daily demand is critical to designing a manufacturing system in which production control, inventory control, and machine tool maintenance are functionally integrated.

Conversion of the job shop system into a flexible, linked-cell system is a design task. See **Figure 5**, Just as design engineers now try to design products which are simpler and easier to manufacture, manufacturing engineers try to design a factory which is simpler to operate.

Most companies "design" their first cell by one of the trial-and-error techniques for expediency in gaining experience in cells.

By grouping similar components into families of parts, a group or set of processes can be collected together to make a family. This is a manufacturing cell. The arrangement of the machines in the cell is defined by the sequence of manufacturing processes. The operations in the cell include all sorts of metal cutting operations, heat treating, inspection, assembly, and even grinding and superfinishing. All are done as steps in one cell that makes all the variations of a component, say for a model of a car.

Most companies begin with a pilot cell using existing equipment so that everyone can see how cells function. It will require time and effort to train the operators, and they will need time to adjust to standing and walking. Simply select a product or group of products that seems most logical. The operators *must be involved* in designing the cell or they will not take ownership. The pilot cell will show everyone how cells operate and how to reduce setup time on each machine .Machines will not be utilized 100%. Machine utilization rate usually improves but may not be what it was in the functional system where *overproduction* is allowed. The objective in manned linked-cell manufacturing systems design is to utilize the people fully, enlarging and enriching jobs, allowing operators to become multifunctional. The operators learn to operate many different kinds of machines and perform tasks that include assembly, quality control, machine tool maintenance, setup reduction, and continuous improvement. (In unmanned cells and systems, the utilization of the equipment is more important because the most flexible and smartest element in the cell, the operator, has been removed and has been "replaced" by a robot.)

The cells are designed in U-shapes or parallel rows so that the workers can move from machine to machine, unloading, checking, and loading parts. **Figure 5** shows an example of a simple manned cell. The cell has one worker who can make a walking loop around the cell in 110 seconds. Therefore, the cycle time for the cell is 110 seconds. Cycle time equals the inverse of the production rate. The machines in the cell are single-cycle automatics, so that they can complete the desired processing untended, turning themselves off when finished with a machining cycle. The operator comes to a machine, unloads a part, checks the part, loads a new part into the machine, and starts the machining cycle by hitting a walkaway switch as he moves to the next machine. The cell usually includes all the processing needed for a complete part or subassembly. The table shows the typical average times for the operator time, human or manual time, and walking time. The times for the machining cycle are given as machining times (MT). Here is the axiomatic design rule for cells. The cell is designed such that the machining time for any part in the family for any machine in the cell is less than the necessary cycle time, CT. The design rule for manufacturing cells is: $MT_{ij} < CT$ *where i = no. of machines in the cell, j = no. of different components made by the cell.* That is, machining times are uncoupled from the cycle time. But, the machining time for the third operation is greater than the necessary cycle time. That is, 180 seconds is greater than 110 seconds. One solution to this problem is to duplicate the operation. The operator alternates between the two lathes, visiting each lathe every other trip he or she makes around the cell. This makes the average MT 180/2 = 90 seconds and less than the cycle time.

Standardized work is the basis for maintaining productivity, quality, and safety at high levels. It provides a consistent structure for performing the tasks in the designated takt time while uncovering opportunities for making improvement in work procedures.

There are three aspects in structuring standardized work in a cell

- Takt time (daily demand)
- Working sequence
- Stock-on-hand

Takt time reflects the pace of sales in the marketplace or what may be called the daily demand. The working sequence is the sequence of operations that is the best way to perform a task. The stock-on-hand is the minimum number of workpieces needed to have on hand in a cell to maintain a smooth flow of work.

Standardized work provides detailed, step-by-step guidelines for every job in the lean shop. Team leaders and operators determine the most efficient working sequence and make continuing improvements—kaizen—in that sequence. Kaizen thus begets new patterns of standardized work.

Cells have many features that make them unique and different from other manufacturing systems. Parts move from machine to machine *one at a time* within the cell. For material processing, the *machines are typically* capable of completing a machining cycle initiated by a worker. The U-shape puts the start and finish points of the cell next to each other. Every time the operator completes a walking trip around the cell, a part is completed. The cell is designed so that this cycle time (CT) is equal to or slightly less than the takt time (cycle time) for final assembly. is referred to as the necessary cycle time. The machining time (MT) for each machine needs only to be less than the time it takes for the operator to complete the walking trip around the cell. Thus, the machining time can be altered without changing the production schedule. Conversely, and much more significantly the production schedule can be altered without changing the machining times. Let's say that again in another way. The L-CMS design permits you to change the final assembly output without having to redo all the subassembly and component supplier schedules.

The cell is designed to make parts *as needed* by downstream processes and operations. There is no overproduction. Overproduction will result in the need to store parts, build huge automatic storage and retrieval systems, transport parts to storage, retrieve the parts when needed, keep track of the parts (paperwork), and so on.

All this requires people and costs money but adds no value. In assembly cells, the cycle time is readily changed by adding or subtracting operators.

In manufacturing cells, there is no need to balance the MTs for the machines. This can be a very difficult task in flow lines (transfer lines). In cells, it is necessary only that no MT be greater than the required CT. The machining speeds and feeds can be relaxed to extend the tool life of the cutting tools and reduce the wear and tear on the machines as long as the MT does not equal or exceed the CT.

The fixtures in the machines are designed to hold the family of parts so rapid easily loaded/unloaded, cannot be loaded incorrectly, and defective parts cannot be loaded.

Between the process steps *decouplers* elements are placed to provide flexibility, part transportation, inspection for defect prevention (pokayoke) and quality control, and process delay for the manufacturing cell. The decoupler element can inspect the part for a critical dimension and feed back adjustments to the machine to prevent the machine from making oversize parts (as the milling cutter wears). A process delay decoupler would delay the part movement to allow the part to cool down, heat up, cure, or whatever is necessary for a period of time greater than the cycle time for the cell. Decouplers and flexible fixtures are vital parts of both manned and unmanned cells.

STEP 3: RAPID EXCHANGE OF TOOLING AND DIES

When cells are formed to make a family of parts, then the problem of changing over the machines from one part in the family to another must be immediately addressed. Therefore, everyone on the plant floor must be taught how to reduce setup time using SMED (single-minute exchange of die). SMED is a four stage methodology developed by Shigeo Shingo to reduce tooling and die exchange times, that is, reduce setup times, see **Figure 6**. A setup reduction team trains the production workers and foremen in the SMED process and demonstrates the methodology on a project, usually the plant's worst setup problem. Reducing setup time is critical to reducing lot size and the idea for SMED is to make the setup process fast and easily done by the operators as part of their routine.

The lean production approach to manufacturing demands that small lots be run. This is impossible to do if machine setups take hours to accomplish. In mass production, the *economic order quantity* (EOQ) formula has been widely used to determine what quantity should run to cost-justify a long and costly setup time. The EOQ was a faulty suboptimal approach that accepted long setup times as a given. Setup times can be reduced, resulting in reduced lot sizes and throughput times while improving the flexibility of the system.

Successful setup reduction is easily achieved when approached from a methods engineering perspective. Much of the initial work in this area uses videotapes with time and motion studies while applying Shingo's SMED rules for rapid exchange of tooling. Setup time reduction occurs in four stages. The initial stage is to determine what currently is being done in the setup operation. The setup operation is usually videotaped and everyone concerned gets together and reviews the tape to determine the elemental steps in the setup. The next stage is to separate all setup activities into two categories, *internal* and *external*. Internal elements can be done only when the machine is not running; external elements can be done while the machine is running. This elemental division will usually shorten the lead time considerably. Stages 3 and 4 focus on reducing the internal time. The key here is that the operators perform all the setups and learn how to reduce setup times by applying simple principles and techniques. If a company must wait for the setup reduction people to examine every process, a lean manufacturing system will never be achieved.

The similarity in shape and processes needed in the family of parts allows setup time to be reduced or even eliminated. Initially setup should be less than 10 minutes (SMED). As the cell matures, the setup times are continually reduced. Reducing the setup time until it is equal to or less than the cycle time (1–2 minutes) for the cell is usually quite easily accomplished. This will permit a significant initial reduction in lot size. The next goal is to get setup times down to around 10–15 seconds, what is commonly called one-touch exchange of dies (OTED), see **Figure 7**.

In the last stages of SMED, it may be necessary to invest capital to drive the setup times below 1 minute. Automatic positioning of workholders, intermediate jigs and fixtures, and multiple duplicate workholders represent the typical kinds of hardware needed. The result is that long setup times can be reduced to under 15 seconds in relatively short order.

When the setup time is down to less than the time needed to load, unload, inspect, deburr, and so on at the machine, the operators can quickly change the machines over from one component to the next. **Figure 8** shows how the setup operation flows through the cell one cycle at a time as the cell is changed over from part A to part B. After each setup, at each machine, defect-free products should be made right from the start. The first part will be good. Ultimately, the ideal condition would be to eliminate setup between different parts. This is called no touch exchange of dies (NOTED).

In summary, the savings in setup times are used to decrease the lot size and increase the frequency at which the lot is produced. The smaller the lot the lower the inventory, creating shorter throughput time and improving quality.

STEP 4: INTEGRATE QUALITY CONTROL

A *multiprocess* worker can run more than one kind of manufacturing process. A *multifunctional* worker can do more than operate machines. This team member is also an inspector who understands process capability, quality control, and process improvement. In the lean shop, every worker has the responsibility and the authority to make the product right the first time and every time and the authority to stop the process when something is wrong. This integration of quality control into the manufacturing system markedly reduces defects while eliminating inspectors. Cells provide the natural environment for the integration of quality control. The fundamental idea is to inspect to prevent the defect from occurring and to never let a defective product leave the cell.

When every worker is responsible for quality and able to use the seven basic tools of quality control, shown in **Figure 9**, the number of inspectors on the plant floor is markedly reduced. Products that fail to conform to specification are immediately uncovered because they are checked or used immediately.

In lean manufacturing every worker is an inspector responsible for quality. What happens when a worker on the assembly line stops the line if they find something wrong? Everyone's attention is focused on the problem holding up production. Problems get solved fast and permanently so the line is not stopped again. *Inspection to prevent the defect from occurring* rather than *inspecting to find* the defect after it has occurred becomes the mode of operation in the lean shop. Ultimately, the concept of *autonomation* evolves (see step 9) which means to automate to prevent the occurrence of defects based on lessons learned from the operation of the cell. Literally, the autonomation means automation with a human touch.

Now here is the fundamental difference between lean production systems and other systems. Through redesign, the cells produce parts one at a time, just like assembly lines. This is called one-piece flow. Within all the production entities, the internal customers operate a *make one, check one ,move one on* basis or MO-CO-MOO. The operator is checking what the previous process produced to assure it is right 100% of the time. Pull cords are installed on the assembly lines to stop the lines if anything goes wrong. Subassembly workers use self-checking and successive checking methodologies to ensure defect work is rooted out. If workers find defective parts, if they cannot keep up with production, if production is going too fast according to the quantity needed for the day, or if a safety hazard is found, they are obligated to stop the line. The problem is fixed immediately. Meanwhile, the other workers maintain their equipment, change tools, sweep the floor, or practice setups; but the line does not move until the problem is solved.

For manual work on assembly lines, the system for tracking defective work is called *andon*. An andon is actually an electric light board that hangs high above the assembly lines so that everyone can see it. When everything is going okay, the lights are green. But, when a worker on the line needs help, the yellow light is turned on. Nearby (multifunctional) workers who have finished their jobs within the allotted cycle time move to assist workers having problems (called mutual assistance). If the problem cannot be solved within the cycle time, a red light comes on and the line stops automatically until the problem is solved. Music usually plays to let everyone know there is a problem on the line.

In most cases the red lights go off within 10 seconds. If the line stops, for restarting, a green light comes on, with all the synchronized processes beginning together. The name for this system is Yo-i-don, which literally means "ready, set, go." Such systems are built on teamwork and a cooperative spirit among the workers, fostered by a management philosophy based on harmony and trust.

Of course there are more ways to control quality than outlined in **Figure 9** but these seven (7) "tools" are fundamental to the integrated process because these tools are used by the operators. Value stream mapping and analyzing the process to understand its behavior is key to finding out what went wrong. By designing the system and all the processes into a single-piece flow methodology, the causes of the defects (the effects) are quickly isolated and identified, thus cures can be readily implemented!

The L-CMS strives for continuous improvement in the processing to reduce the variability (or spread in measurements about the process mean).Thus reducing the process variability improves its process capability as shown in **Figure 10**. In lean manufacturing, the continuous improvement aspects are driven by the systematic removal of inventory—see step 7 for further discussion.

So here we understand the key to achieving superior quality in lean manufacturing lies in isolating process steps in a serial fashion in the cells. There is one process for each step. Multiple processes for the same step will increase the process variability. The outcome from each step is checked before the component is moved to the next step. The operators have complete feedback of each step in the processing. This feedback involves all of the operators senses, hearing, sight, smell, touch, and even taste, making them superior to machines. They are on the front line for problem identification and resolution.

STEP 5: MAKE OUTPUT PREDICTABLE: INTEGRATE PREVENTIVE MAINTENANCE

Making machines operate reliably begins with the installation of an integrated preventive maintenance program, giving workers the training and tools to maintain their equipment properly The excess processing capacity obtained by reducing setup time allows operators to reduce the equipment speeds or feeds and to run processes at less than full capacity. Reducing pressure on workers and processes to produce at full speed or maximum capacity fosters a drive to produce perfect quality.

Producing to takt time, at the pace of customer demand, in a balanced system (step 1) defines the appropriate pace of production for the workers and the processes. Prior to lean, companies thought they could lower cost by running machines as fast as possible, all of the time. Lean recognizes that such strategies result in overproduction and poor quality.

The multifunctional operators are trained to perform routine machine tool maintenance. Just adding lubricants (oiling the machine), checking for wear and tear, replacing damaged nuts and bolts, routinely changing and tightening belts and bolts, and listening for telltale whines and noises that signify impending failures can do wonders for machine tool reliability. The maintenance department must instruct the workers on how to do these things and help them prepare the routine checklists for machine maintenance. The workers are also responsible for keeping their areas of the plant clean and neat. Thus another function that is integrated into the manufacturing system is housekeeping. The Five-S strategy for housekeeping: The five Ss are:

Seiri-sifting-organization: Analyze what is available for the task, determine what is required to complete it, and discard what is unnecessary. Anything extra is wasteful. For example, having extra tools, materials, pencils, and paper is waste and should be eliminated.

Seiton-sorting-arrangement: Once the minimum requirement is determined, there must be “a place for everything and everything in its place.” Assign a location for essential items. Make the workplace self-explanatory so everyone knows what goes where. Eliminate confusion and lost time associated with searching for items out of their proper place.

Seiso-sweeping-cleaning: Once the work site is organized and arrangements are completed, tools must be kept clean and easily obtainable so there is no fumbling or lost time. If something goes wrong, a backup tool should be available, in proper working condition, and stored exactly where it can be readily found.

Seiketsu-spic-and-span-hygiene: The working environment should be as clean as possible. Hygiene usually complements the other aspects of detailed housekeeping. Effective organization and work arrangement is reinforced by keeping the entire area as clean as possible, particularly the floor.

Shitsuke-strict-discipline: The other four Ss must be pursued with strict discipline. The rules must be followed and become part of the daily routine. It seems the fifth S is the most difficult to follow. Working areas, tooling, and processes begin as organized, arranged, and clean, but over time the workplace becomes messy and deteriorates. This is the second law of thermodynamics in action on the factory floor. All systems degrade with time unless maintained. Daily discipline greatly enhance the Five-S tool.

The Five Ss help to identify problem areas and waste. However, lean production depends on everyone’s active involvement. Thus, every member of the factory must follow the Five S principles before results are noticed and sustained on a daily basis.

Naturally, the machines still need attention from the experts in the maintenance department, just as the airplane is taken out of service periodically for engine overhaul and maintenance. One alternative here is to implement two 9-hour shifts (8 work hours plus 30 minutes for lunch plus two 15-minute breaks) separated by two 3-hour time blocks for machine maintenance, tooling changes, restocking, long setups, overtime, earlytime, and so on. This is called the 8-4-8-4 scheme. The main advantage that equipment has over people is that it can decrease variability, but it must be reliable and dependable. Smaller machines are simpler and easier to maintain and therefore are more reliable. Small machines in multiple copies add to the flexibility of the system as well. The linked cell system permits certain machines in the cells to be slowed down and therefore, like the long-distance runner, to run farther and easier without breakdown. Many observers of the lean shop come away with the feeling that the machines are "babied." In reality, they are being run at the pace needed to meet the daily demand.

True lean producers build and modify much of their manufacturing process technology. This is where they become unique and proprietary .Machine tools are equipped with vibration sensors, temperature monitors, coolant/lubricant sensors, and of course, process controls for single cycle automatic operation of the machines and walkaway switches to start the machining cycles. The sensors provide early warnings of problems or can shut off the machine if a problem is detected. In addition, multiple copies of machines are made for making the similar products. Suppose you are the lean supplier for steering gears. Your plant has a cell for making rack bars for a rack and pinion steering gear. The Mitsubishi manufacturing cell for racks makes 6 different racks for their SUV. In the same plant, the Toyota cell makes rack bars for Camry and Avalon and can make 10 different kinds of rack bars in the same cell. The two cells are similar in their design because the rack bars require a similar set of processes. In the event of a machine failure in the Mitsubishi cell, a machine from the Toyota cell can be borrowed, modified, and used during second shift in the Mitsubishi cell. Processing capacity and capability is replicated in proven increments. Because the increment (the cell) has an optimal design, this is an economic choice as well as having the security of dealing with a proven manufacturing process technology. Modifying existing equipment shortens the time needed to bring new technology on stream. Manufacturing in multiple versions of small-capacity machines retains the expertise and permits the company to keep improving and mistake-proofing the process. In contrast to this approach is the typical job shop, where a new supermachine (large, expensive, multiple operation) would be purchased and installed when product demand increases. That is, many companies try to increase capacity by buying new, untried manufacturing technology that may take months, even years, to debug and make reliable.

STEP 6: INTEGRATING PRODUCTION CONTROL (PC)

The function of the people who work in production control is to schedule the manufacturing system which means they determine *where* the raw materials, purchased parts, and subassemblies are to go, *when* they should go there, and *how many* should go at any point in time. In short, production control determines where, when and how many. In the traditional mass production system, the PC function is very labor intensive, and many people have tried to computerize it using software called manufacturing or enterprise resources planning, or MRP. Many companies' experience with these computerized control systems has been that of great expense, wasted time, disappointment, and frustration. Why? Because these software packages were designed for planning, not control. The lean manufacturing approach redesigns the manufacturing system to integrate the production control functions into the system design. Steps 1 through 5 provide the physical stage to integrate production control functions. This is typically achieved by the use of kanban.

Integration of production control is achieved by linking the cells, subassemblies, and final assembly elements utilizing kanban. The layout of the manufacturing system will define paths that parts can take through the plant. By connecting the elements with kanban links, the need for route sheets is eliminated because the job shop is eliminated. Here is the design rule for the kanban linking. $K = \frac{L \times DD + SS}{a}$ where SS is the safety stock, a is the number of parts in each container, DD is the daily demand and L = lead time. Lead time accounts for all the waiting, delay and transportation time for a cart to make a trip around the link. The subassemblies and component parts (i.e., the in-process inventory) move within the structure on clearly defined paths. All the cells, processes, subassemblies, and final assemblies are connected by the kanban links, pulling material to final assembly. This is the integration of production control into the manufacturing system, forming an L-CMS.

Kanban is a visual control system that is only good for lean production with its linked cells and its namesakes; it is not good for the job shop. Linking the cells together provides control over the route that the parts must take (while doing away with the route sheet), controls the amount of material flowing between any two points, and provides information about when the parts will be needed.

In the dual card kanban system, there are two kinds of kanban: *withdrawal* (or conveyance) *kanban* (WLK) and *production-ordering kanban* (POK). The WLK kanban is the link connecting the output side of one cell with the input point of the next cell (see **Figure 11**). This link is filled with carts or containers that hold parts in specific numbers. Every cart holds the same number of parts and has one WLK and one POK. If there are K carts, then

Maximum inventory = K (number of carts) x a (number of parts in each cart).

The arrival of an empty cart at the manufacturing cell initiates the order (the POK) to make more parts to fill the cart. The WLK kanban cards tell the material handler where to take the parts. Suppose the link has six carts and each cart holds 50 parts, the maximum inventory (WIP) is 300 parts.

The same kind of link connects the subassembly cells to final assembly. All the other cells in an L-CMS are similarly connected by the pull system for production control.

STEP 7: INTEGRATING INVENTORY CONTROL

All of the material in a manufacturing system is considered inventory. There are three basic types—raw material, in-process or work-in-process (WIP), and finished goods. Step 7 involves the integration of the control of the in-process inventory. In the L-CMS system, the work-in-process (WIP) inventory in the system is held in the links. The WIP inventory has been analogized to the water in a river, as shown in **Figure 12**. A high river level is equivalent to a high level of inventory in the system. The high river level covers the rocks in the riverbed. Rocks are equivalent to problems. Lower the level of the river (inventory) and the rocks (problems) are exposed. This analogy, developed by Taiichi Ohno and published by Shigeo Shingo, is quite accurate. In lean manufacturing, the problems receive immediate attention when exposed. When all the rocks are removed, the river can run very smoothly with very little water. However, if there is no water, the river has dried up. The notion of zero inventory is incorrect. While zero defects is a proper objective, zero inventory is not possible. (Within the cell, parts are already handled one at a time, just as they are in assembly lines. The material in the cell is called the stock-on-hand [SOH] so technically there is no inventory in the cells [hence zero inventory].)

The idea is to minimize the necessary WIP between the cells. This is how the inventory in a lean manufacturing system is controlled. The level of WIP between cells, subassembly, and final assembly is actually controlled by team leaders in the various departments. The control is integrated and performed at the point of use. Here is what team leaders do. Suppose that there are six carts in the link and that each cart holds 50 parts. The maximum inventory in this area is therefore 300 parts. The foreman goes to the stock area outside the cell and picks up the kanban cards (one WLK, one POK), which puts one full cart of parts out of commission. The (maximum) inventory level is now 250 parts. The foreman waits until a problem appears. When it appears, the foreman immediately restores the kanban, which restores the inventory to its previous level. The cause of the problem may or may not be identified by the restoration of the inventory, but the condition is relaxed until a solution can be enacted. Once the cause of the problem is identified and solved, the foreman repeats this procedure. If no other problems occur, the foreman then tries to drop the inventory to 200 parts. This procedure is repeated daily in the links all over the plant. After a few months, the foreman may be down to the three carts of 50 parts. Over the weekend the system will be restored to six carts between the two points, but this time each cart will hold only 25 parts. If everything works smoothly, with the reduced cart quantity, the foreman will soon remove a cart to see what happens. More than likely, some setup times will need to be reduced. In this way, the inventory in the linked-cell system is continually reduced, exposing problems. The problems are solved one by one. The teams work on solving the exposed problems including long setup times. The effect on the system of removing inventory is to continuously improve the TPT. This is how continuous improvement works in the lean production factory.

The minimum level of inventory that can be achieved is a function of many factors: the quality level, the probability of a machine breakdown, the length of the setups, the variability in the manual operations, the number of workers in the cell, parts shortages, the transportation distance, and so on. It appears that the minimum number of carts is three, and, of course, the minimum lot size is one. The significant point here is that inventory becomes a controllable independent variable rather than an uncontrollable variable dependent on cravings of the users of the manufacturing system for more inventory.

STEP 8: INTEGRATING THE SUPPLIERS

In L-CMS system design one tries to reduce the number of suppliers and have a single source for each component or subassembly. Suppliers are educated and encouraged to develop their own lean production system for superior quality, low cost, and rapid ontime delivery. They must be able to deliver perfect parts downstream to their customers when needed and where needed without incoming inspection. The linked-cell network ultimately should include every supplier. Suppliers become remote cells in the L-CMS.

In the traditional job shop environment, the purchasing department permits its suppliers to make weekly/monthly/semiannual deliveries with long lead times—weeks/months are not uncommon. A large safety stock is kept just in case something goes wrong. Quantity variances are large and late and early deliveries are the norm. The situation leads to expediting, where people try to find the parts that are delaying assembly and get them moving (this is a total waste).

In mass production, as a hedge against supplier problems, multiple sources are developed. The suppliers' profit margins are cut thin and the plant is unreliable and may be in jeopardy of bankruptcy. Meanwhile, the purchasing department may claim that pitting one supplier against another gives the company a competitive advantage and lower cost parts.

The lean manufacturing approach to suppliers is quite different. Just-in-time purchasing is a program of continual long-term contracts and improvements. The buyer and supplier work together to reduce lead times, lot sizes, inventory levels, and unit cost while improving quality. Both the supplier and the customer become more competitive in the world marketplace.

In this environment, longer-term (18–24 months) flexible contracts are drawn up with three or four weeks lead time at the outset. The buyer supplies updated forecasts every month that are good for 12 months, commits to long-term quality, and perhaps even promises to buy out any excess materials. Exact delivery is specified by midmonth for the next month. Frequent communication between the buyer and the supplier is typical. Kanban controls the material movement between the supplier and the buyer. The supplier is a remote cell. Long-range forecasting for 6months to 1 year is utilized. As soon as the buyer sees a change, the supplier is informed; this knowledge gives the supplier better visibility instead of a limited lead time view. The supplier has *build-schedule stability* (not "jerking" up and down of the build-schedule) an outcome of leveling final assembly.

The buyer moves toward fewer suppliers, often going to local, sole sourcing. Frequent visits are made to the supplier by the buyer, who may also supply engineering aid (quality, automation, setup reduction, packaging, and the like) to help the supplier become more knowledgeable on how to deliver, on time, the right quantity of parts that require no incoming inspection. This is truly *technology transfer*. The suppliers learn about lean manufacturing from the customer. The buyer and the seller work together to solve problems.

The advantages of single sourcing are that resources can be focused on selecting, developing, and monitoring one source instead of many. When tooling dollars are concentrated in one source, there is a huge savings in tooling dollars. The higher volume should lead to lower costs. The supplier is more inclined to do special things for the buyer. The buyer and the supplier learn to trust one another. Quality is more consistent and easier to monitor when there is a single source as there is less variability in the components.

Finally there is the aspect of proprietary processes. Toyota and other users of lean manufacturing have published very little about the manufacturing/assembly cells. Why? This is where the unique process technology exists which give companies like Toyota and Honda the edge in manufacturing. They develop the machine tools and the processes inhouse rather than buy them from a machine tool supplier. Machine tool suppliers cannot keep secrets. Lean manufacturers gain their competitive edge by developing unique manufacturing process technology and keeping it "locked up" in the cells. **Table 3** summarizes the key points in managing a supplier plant. This list was obtained from the plant manager at a first tier supplier to Toyota Camry.

STEP 9: AUTONOMATION (NOT JUST AUTOMATION)

Autonomation means the autonomous control of quality and quantity. Stop everything immediately when something goes wrong; control the quality at the source instead of using inspectors to find the problem that someone else may have created. The workers in the lean factory inspect each other's work, called successive checking. Taiichi Ohno, former vice president of manufacturing for Toyota, was convinced that Toyota had to raise its quality to superior levels in order to penetrate the world automotive market. He wanted every worker to be personally responsible for the quality of the piece part or product that was produced (called source or self-checking).

The need for automation simply reflects the gradual transition from manual to automated functions. Some people think of this as computer integrated manufacturing (CIM).Others recognize that people are the most important (and flexible) asset in the company and see the computer as just another tool in the process but not the heart of the system. For example, inspection devices are placed in the machines (source inspection) or in devices (decouplers) between the machines, so the inspection is performed automatically. This generally reduces the cycle time in the cell. Remember, the idea is to prevent the defect from occurring rather than to inspect to find the defect after the part is made. Inspection by a machine instead of by a person may be faster, easier, and more repeatable but it may not be able to replace laying hands on the parts.

Autonomation means inspection becomes part of the production process and does not involve a separate location or person to perform it. Parts are 100% inspected by devices that either stop the process if a defect is found or correct the process before the defect can occur (requiring feedback to the controller). The machine may shut off automatically when a problem arises to prevent mass production of defective parts. See **Figure 13** for an examples of a pokayoke devices (which prevent defects). The machine may also shut off automatically when the necessary parts have been made to prevent overproduction. This is part of inventory control.

Over time the entire L-CMS is being continuously improved through changes in the system design. The interim manufacturing cells are gravitating toward lean manufacturing cells wherein many of the machine tools are custom built for the cells. The aspect of the L-CMS design strategy will be briefly discussed later in this section.

TABLE 3. Managing the Lean Production System (LPS)*	
The Lean Production System is the basic philosophy and concepts used to guide production processes and environment. The LPS includes the linked-cell manufacturing system (cells linked by a kanban pull system), the five S's, standard operation, the seven tools of QC, and other key organizational elements.	
Kanban pull system (see step 6)	The production processes that use a card system, standard container sizes, and pull versus push production to accomplish just-in-time production.
Five S's (*Seiri, Seiton, Seiketsu, Seis Shitsuke*) (see step 5)	The five S's are proper arrangement, orderliness, cleanliness, cleanup, and discipline.
Standard operation in manufacturing cells (see step 2)	The production process used by technicians that combines people and process. The components of standard operation include cycle time, work sequence, and standard stock-on-hand in the cells.
Morning meeting	A daily meeting held for the purpose of sharing production and safety information, quite often by a quality circle.
Key points: Process sheets	The process sheets, which are visually posted at each workstation, detail the work sequence and most critical points for performing the tasks.
Tooling parts: Changeover and setup (see step 3)	The machine setup that takes place when an assembly line changes products.
Seven tools of quality (see step 4)	The seven tools to quality are: Pareto's diagram, check sheets, histograms, cause-and-effect diagram, run charts for individuals, control charts for samples, and scatter diagrams.
Production behavior	Rules that include information on personal safety, safety equipment, clothing, restricted areas, vehicle safety, equipment safety, and housekeeping.
Visual management	East line in the plant has a complete set of charts, graphs, or other devices, like Andons, for reporting the status and progress of the area.
* From a plant manager of a first tier supplier to Toyota	

STEP 10: RESTRUCTURE THE PRODUCTION SYSTEM

Once the factory (the manufacturing system) has been restructured into a linked-cell manufacturing system and the critical control functions well integrated, the company will find it expedient to restructure the rest of the company. This will require removing the functionality of the various departments and forming teams, often along product lines. It will require the implementation of concurrent engineering teams to decrease the time needed to bring new products to market. This movement is gaining strength in many companies and the idea is to restructure the production system to be as waste free as the manufacturing system.

Clearly, shifting from one type of manufacturing system design to another will affect product design, tool design and engineering, production planning (scheduling) and control, inventories and their control, purchasing, quality control and inspection, and, of course, the production worker, the foreman, the supervisors, the middle manager, and so on, right up to top management. Such a conversion cannot take place overnight and must be viewed as a *long-term transformation* from one type of *production system* to another. This kind of downsizing can be very traumatic for the business part of the company and usually has a negative impact on the morale of the company. This is why lean manufacturing is difficult to implement.

Therefore, step 10 recognizes the need for the rest of the company to reorganize (get lean).This effort often begins with building *product realization teams* designed to bring new products to the marketplace faster. In the automotive industry, these are called *platform teams* and are an example of concurrent engineering. Platform teams are composed of people from design engineering, manufacturing, marketing, sales, finance, and so on. As the notion of team building spreads and the lean manufacturing system gets implemented, it is only natural that the production system will follow suit. Unfortunately, many companies are restructuring the business part of the company without having done the necessary steps 1 through 8 to get the manufacturing system lean and efficient. Downsizing the enterprise without simplifying and redesigning the manufacturing system can lead to difficult times for the enterprise. Other companies have tried to automate their way to productivity without first simplifying the system and integrating the function. More difficult times are the outcome.

The design of the manufacturing process technology must be done early in the product development process. The manufacturing process technology within the manufacturing cells must be part of (i.e., elements within) a well-designed, integrated manufacturing system. Flexibility in the design of an integrated manufacturing system means it can readily accept new product designs. Flexibility in the process technology means the process can readily adapt to product design changes and be engineered to accept new products.

LEAN MANUFACTURING CELL DESIGN

Product design (for manufacture and assembly) and MSD must go hand-in-hand, striving for customer satisfaction. The functional requirements of a good MSD are flexibility, controllability, efficiency, and uniqueness. The factors needed to achieve satisfactory usage of the manufacturing system by the internal customers (the workers) are safety, equipment reliability, ergonomically sound equipment, and good service from engineering. Ergonomically sound equipment means that the processes are designed to be easy to operate and easily maintained, are fail-safe, and are not dirty, noisy, labor-intensive, or hazardous.

In the lean manufacturing system, manufacturing engineers are responsible for designing, building, testing, and implementing the manufacturing equipment that will be used by the internal customers in the manufacturing cells (machine tools and processes, tooling [workholders, cutting tools] and material handling devices [decouplers]). The equipment is simple and reliable and can be easily maintained. In general, this flexible, dedicated equipment is built in-house or purchased from contractors and modified for the needs of the cell.

Many companies understand that it is not good strategy simply to buy the manufacturing process technology from another company and then expect to make an exceptional product using the same technology as the competitor. When the process technology is purchased from outside suppliers, any uniqueness aspects will be quickly lost. The lean company must perform research and development (R&D) on manufacturing technologies as well as manufacturing systems in order to produce effective and cost-efficient products. However, an effective, cost-efficient manufacturing system makes R&D in manufacturing process technology pay off.

The proprietary part of lean manufacturing is designing and building machines and material handling equipment (decouplers) and tooling to meet the needs of the cell and the system. Machines are typically single-cycle automatics but may have capacity for process delay.

ERGONOMICS OF LEAN MANUFACTURING CELLS

Ergonomics deals with the mental, physical, and social requirements of the work and how the work is designed (or modified) to accommodate the human limitation. For example, are the machines in the cell designed to a common height to minimize lifting of parts? Are transfer devices designed for easy slide on/slide off? Are automatic steps equipped with interrupt signaling devices to help the worker monitor the process? When the job is defined as primarily loading/unloading, ergonomic concerns with lifting and placing parts in machines and operating workholding devices must be addressed. In these systems human performance in detecting and correcting cell malfunctions will establish utilization and thus production efficiency. The design of machines for maintainability and diagnostics is critical. The original designer of the cell must incorporate ergonomic issues initially rather than trying to come back later to implement fixes. However, the cell design with its great variety in sequential tasks is ergonomically sound and few repetitive injuries are produced.

Table 4 provides ergonomic cell design considerations:

- Uniform loading heights
- Minimum reach (bending) into machine
- Providing access to machine from the back
- Position of load/unload decoupler (when part requires a two-hand load)
- Location of walkaway start switches
- Eliminating machine obstructions in aisle
- Part weight, size, shape, burrs, finish, etc.

Table 4 Ergonomics – Lean Production Manufacturing Cell Ergonomic Advantages

● Less Muscular Fatigue		
- CMS standing, waling worker	Venous pooling	Better circulation
- Lower heart rates	Part weight, size, shape, burrs, etc.	
● Less CTD Hazards		
- Non-repetitive movements	Forces exerted	Better posture
● Better Man/Machine Interface		
- Adjustable height work station	Controls/Displays compatibility	Scientifically designed tools
- Self aligning	EZ access (minimum reach into machines)	Self inspection
- Location of walkaway switches	Access to machine from the back	Location of decouplers
● Better interface with system		
- Streamlined parts flow	More frequent moves	Minimum twisting
- Minimal lot sizes		

WHY LEAN MANUFACTURING PROGRAMS FAIL

There should always be a champion or take-charge person who gets behind the program and sees it through. Lean manufacturing implementations will fail if management loses interest.

Problems in quality will prevent any real reduction in inventory and lead times. If the company cannot get to zero defects and zero breakdowns, they will not get to lean manufacturing.

Watch out for management (managers) with hidden agendas. If the upper management already knows in advance what solution they want and uses the lean process to direct the employees to their (management) desired ends, then the employees will tire of game playing and lose interest.

Middle management opposition will stop the lean manufacturing. The engineers, quality or MRP folks come to believe that the effort is a reflection on their expertise or competence and try to quietly sabotage the program. Their involvement in planning, data analysis, and status reviews must be assured . This problem also occurs with supervision if they are not carefully brought into the effort.

Systems changes are inherently difficult to implement. Changing the design of the entire manufacturing system is a huge job. Even more critical is that changes at the factory floor level will force changes for the entire enterprise. Companies spend freely for new manufacturing processes but not for new manufacturing systems. It is easier to justify new hardware for the old manufacturing system than to rearrange and modify the old hardware into a new manufacturing system (linked cells). However, anyone with capital can buy the newest equipment, often creating another island of automation.

Converting to linked cells will free up additional capacity (setup time saved) and capital (funds not tied up in inventory), but such conversions are long term projects (lean is journey) and will require expenditure of funds for equipment modifications and employee training in quality, maintenance of machine tools, setup reduction, problem solving, and so forth.

The top management of the company may lose interest if they don't see quick results or get involved in some new fad which dissipates support for lean manufacturing. Generally, few of the companies have long range plans and programs that support concepts like lean manufacturing. Top management tends to manage for quarterly results and immediate fixes. Therefore it is critical that the steps outlined here are followed for a successful implementation of lean manufacturing.

Decision making is choosing among the alternatives in the face of uncertainty. The greater the uncertainty, the more likely that the "do-nothing" alternatives will be selected. The fear of the unknown can lead to uncertainty. In addition, many managers harbor faulty criteria for decision making. Decisions should be based on the ability of the company to compete (quality, reliability, unit cost, delivery time, flexibility for product or volume change) rather than on price alone. Getting the internal customers (production workers) involved in the decision making process is a significant change and critical to getting them committed to the new standardized work methods required for lean manufacturing.

SUMMARY

There are many who believed that the only way in which manufacturing companies can compete is to automate, robotize, and computerize. This is the Computerated Integrated Manufacturing or CIM concept which tries to achieve integration through computerization and automation of pieces of the mass production system. Lean manufacturing is a different approach. It calls for redesigning the mass production system. The conversion of final assembly to mixed model coupled with the development of manufacturing and assembly cells is just the first step in the manufacturing systems design. Lean manufacturing should be implemented prior to any efforts to computerize the system. So the winning manufacturing strategy is first redesign the manufacturing system so the critical control elements are already integrated, then automate to achieve superior quality.

We hear a lot of talk today about continuous improvement. Continuous improvement requires the continuous redesign of the manufacturing system. We hear a lot of talk about technology transfer (TT). Technology transfer happens when buyers share their experience in L-CMS with their suppliers on a one to one basis (step 8).

The lean factory is based on a different design for the manufacturing system in which the sources of variation in time and quality are attacked and the delays and defects in the system removed. In summary, the next generation of American factories (the factories with a future) will be designed with manufacturing and assembly cells linked together with a pull system for material and information control. In this L-CMS, downstream process will dictate upstream production rates. The L-CMS design simplifies the manufacturing system, integrates the critical control functions before applying technology (automation, robotization, and computerization), avoids risks, makes automation easier to implement, and most importantly, provides a system that fosters continuous improvement of the work (and the workplace) by the people who do the work.

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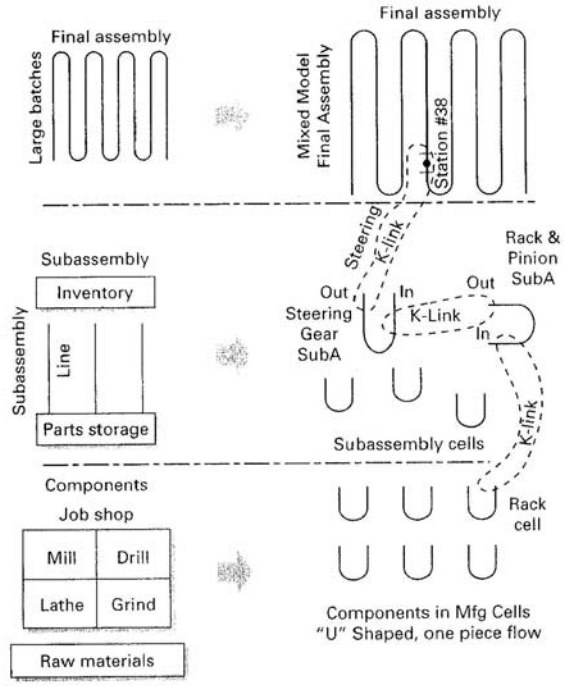


Figure 1 The manufacturing system design called "mass production" produces large volumes at low unit cost. It can be restructured into a lean manufacturing system design to achieve single-piece flow, one of the requirements of a L-CMS design. On the right is a manufacturing cell with a small transfer serving one station in the cell.

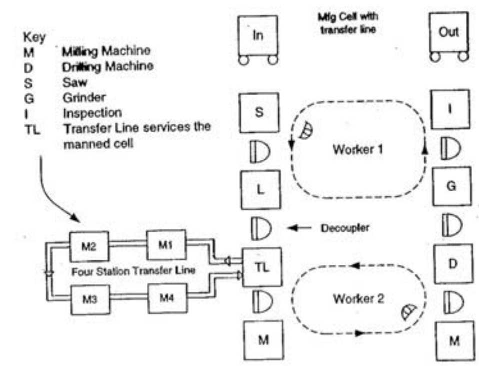
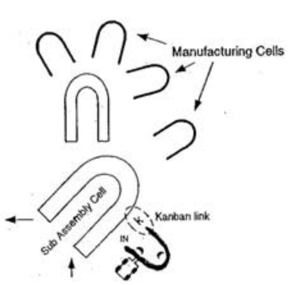
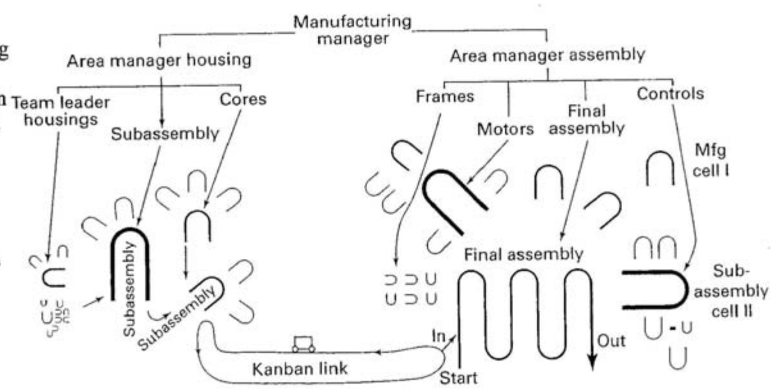
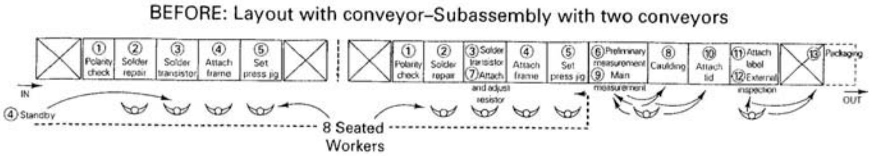
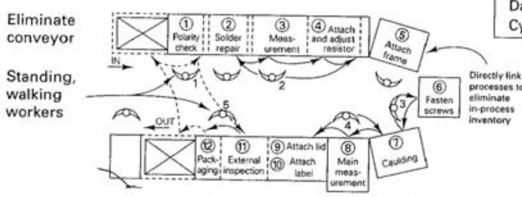


Figure 2 The linked-cell manufacturing system has many manufacturing and subassembly cells connected by kanban links to final assembly. The links hold the inprocess inventory.









Measurable Parameters

	Before:	After:
Output	700	1056 units/shift
In-process inventory	750	8 units
Personnel	10	8 operators
Daily output per person	70	132 units
Cycle time	0.60 minute	0.43 minute

Figure 3 The traditional subassembly line using conveyors can be redesigned into a U-shaped cell. The cell uses walking operators.

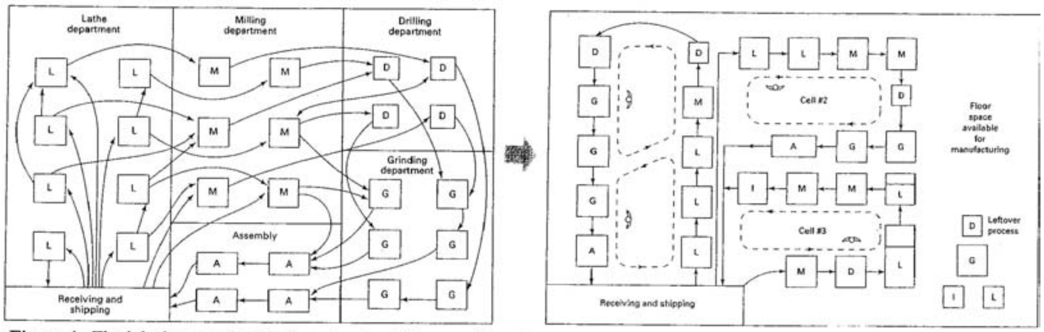
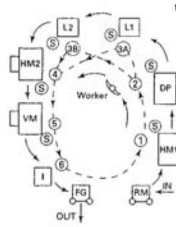


Figure 4 The job shop, on the left, is restructured into manufacturing cells which build families of components.

Interim cells are made up of single cycle automatic machine tools designed for job shop but modified for use in the single piece flow cells.



Work Sequence	Name of Operation	Time: Manual	Time: Walking	Time: Machine
①	Mills ends HM1	12"	5"	30"
②	Drill hole DP	15"	5"	20"
③A or ③B	Turn, bore L1 or L2	13"	3" 5"	180"
④	Mill flats HM2	12"	5" 3"	20"
⑤	Mill steps VM	13"	7"	30"
⑥	Final inspect-I	15"	5"	–
		80"	30"	280"

Key:
DP = Drill Press
L = Lathes
FG = Finished goods
RM = Raw material
HM = Horizontal milling machine
VM = Vertical milling machine
—— Material flow
– – – Operator's path
Ⓧ Operation sequence
Ⓢ Walk-away switch

Takt Time = 2 minutes
Cycle Time = 80 sec + 30 sec = 110 sec
Longest Machining Time = 180 sec
Total Machining Time = 280 sec per part

All machines in the cell are single cycle automatics, processing unattended while the operator is doing manual operations (unload, load, inspect, and deburr) at other machines or walking from machine to machine. The time to change tools and workholders (perform setup) is not shown.

Figure 5 Example of an interim manned cell part of an L-CMS. This cell operates with six machines and one multifunctional worker. The lathe operation, #3, is duplicated.

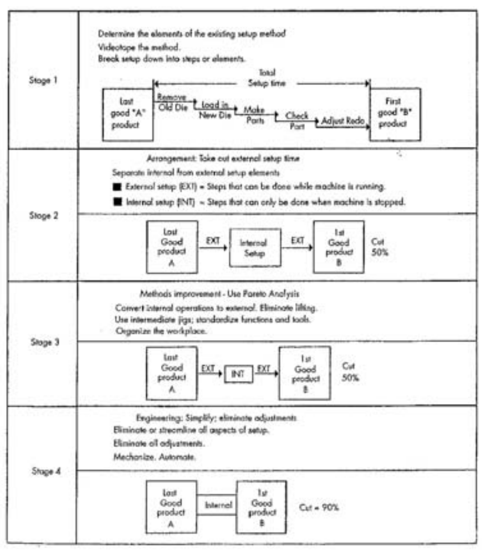
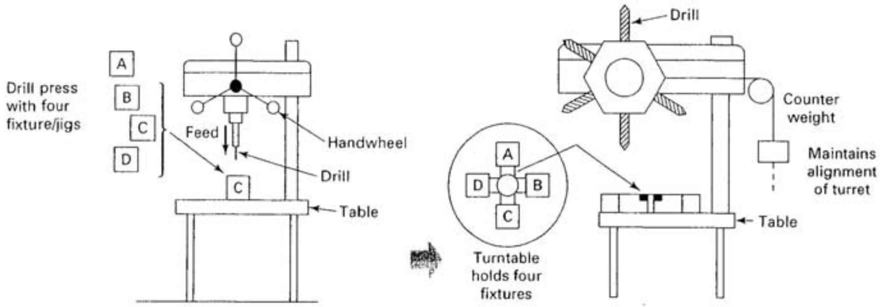


Figure 6 The Four Conceptual Stages of single-minute exchange of dies, SMED, after Shingo. *Source: Lean Manufacturing Systems and Cell Design, J T. Black, Steve L. Hunter, SME 2003.*



In the job shop, a machine tool with four different fixtures or jigs would need four different setups, each consisting of changing fixtures or jigs and alignment of each.

In the manufacturing cell the four fixtures are mounted on a turntable and are permanently aligned to the spindle when locked in position. A multiple tool turret replaces single spindle. Automatic down feed replaces hand wheel, so the machine is a single cycle automatic.

Figure 7 The machines in the interim cell are modified to process the family of parts, reducing setup time to 2 or 3 seconds.

	Four Processes in the Cell			
Cycles Through the Cell	Machine 1	Machine 2	Machine 3	Machine 4
1	A	A	A	A
2	A (last A part)	A	A	A
3	Setup change	A (last A part)	A	A
4	B (first B part)	Setup change	A (last A part)	A
5	B	B (first B part)	Setup change	A (last A part)
6	B	B	B (first B part)	Setup change
7	B	B	B	B (first B part)
8	B	B	B	B

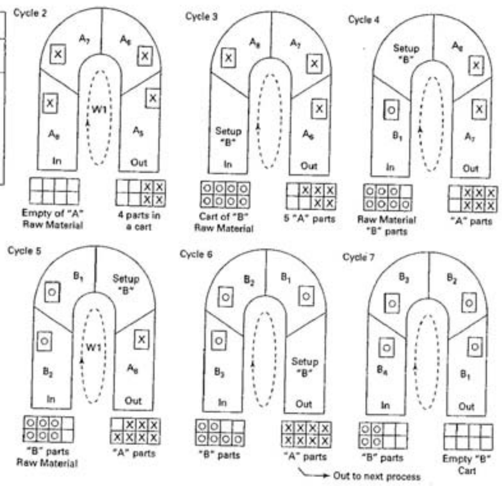


Figure 8 Setup flows through the cell one station at a time.

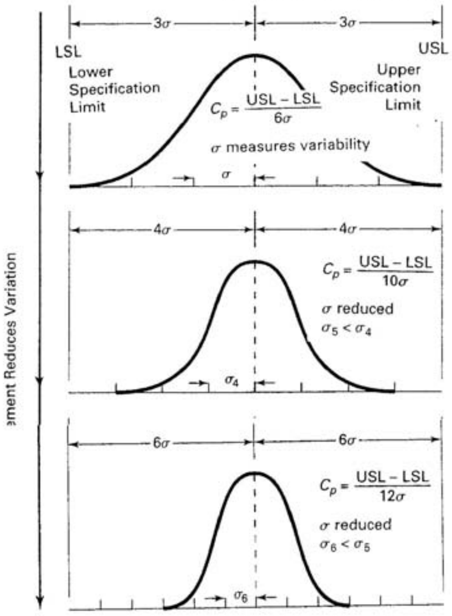


Figure 10 To achieve six sigma capability from three sigma capability, the precision of the process must be greatly improved, reducing σ, the process standard deviation which measures variability.

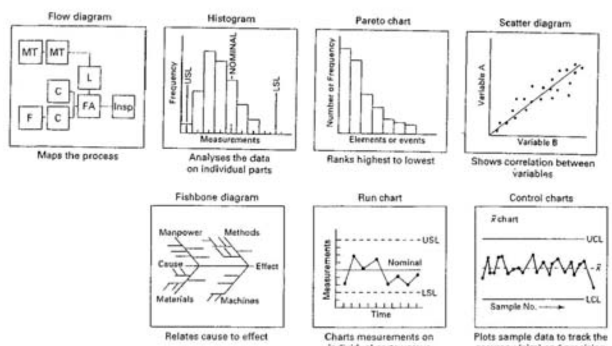


Figure 9 The seven (7) tools of quality control used by the operator.

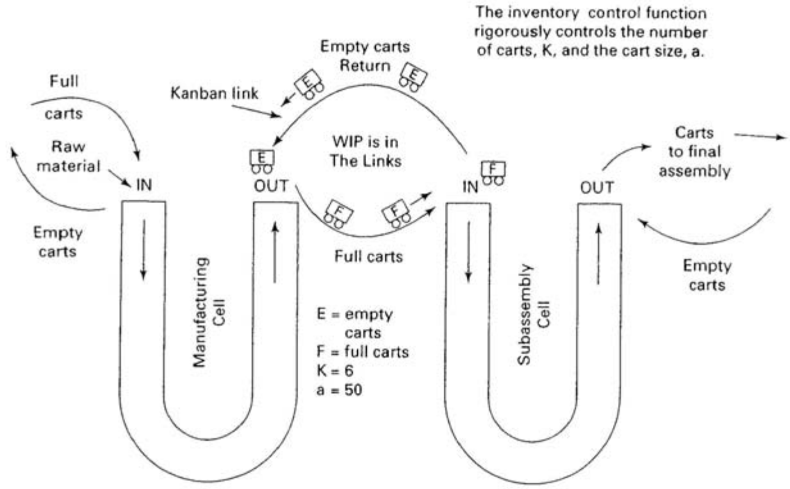


Figure 11 Cells are linked by a kanban system. The arrival of an empty container at the manufacturing cell is the signal to produce more parts.

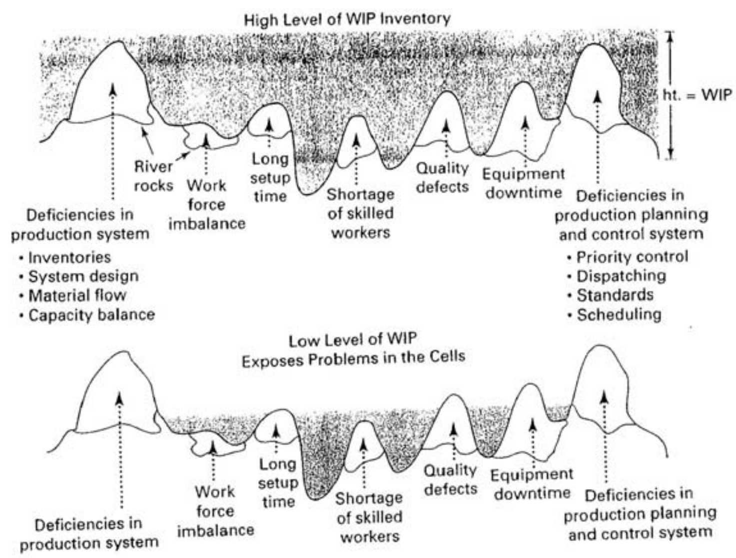


Figure 12 Lowering the level of inventory in the links uncovers the problems.

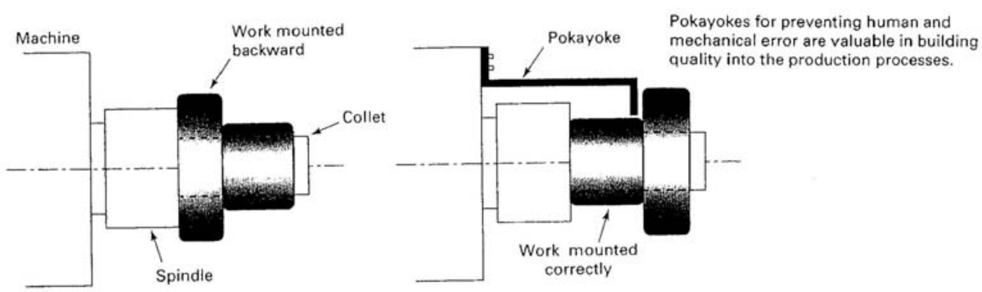


Figure 13 Pokayoke devices prevent defects. (a) On the left, the operator(s) can mount the workpiece backward. The pokayoke device prevents that defect.