PRODUCTION SYSTEM DESIGN AND ITS IMPLEMENTATION IN THE AUTOMOTIVE AND AIRCRAFT INDUSTRY

by

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ABSTRACT

Like design in any discipline, if the fundamental nature of the design is unsound, only limited improvements can be made. In manufacturing, this means that the possibility of arriving to a highly integrated and well rounded manufacturing system is rather remote. The purpose of this thesis is to define the design attributes necessary to design new or convert existing production systems to ones that supports and uses the principles of lean manufacturing and to develop a methodology for implementing the design principles developed.

This thesis is composed of three main sections. First, a case study of two automotive suppliers, one fashioned with a traditional production job shop mentality in mind, the other espouses many lean manufacturing principles. From the case study, the benefits in terms of investment, throughout time, quality, flexibility, direct and indirect labor, and customer responsiveness will be obtained. The second section consists of using a systematic approach to evaluate and understand the requirements and design attributes of a Lean Production System in the automotive industry as well as the applicability of those attributes to the aircraft industry, specifically to three aircraft engine manufacturers. The approach used systematically relates the desired design outcomes (known as functional requirements in axiomatic design terminology) to the design principles and design parameters that are used to achieve the desired result. The third and last section embodies the development of a methodology for implementing Lean Production System (new or existing ones). A case study demonstrating the applicability of the methodology to a low volume-high mix company is presented.

Once the principles and policies of a lean production system design are well understood, the design attributes could be generalized to other production systems, whether aircraft, automotive or make-to-order industries.

Thesis Supervisor:
David S. Cochran,
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1 Introduction

1.1 Background

Though much attention has been given to the design of manufacturing systems, in practice most efforts still remain empirically based. This is surprising given the substantial capital investment required for new manufacturing systems. There is little consensus on the right approach to design the most efficient and most effective manufacturing system. For this reason, when a company wants to become "lean" or wants to increase the production and become more efficient, the company will introduce numerous concepts developed by Toyota and others. The problem is that companies do not know the order in which to implement the "lean changes". In addition, the cause and effect relationship of lean practice implementation is not well understood. The result is that companies do not know why they are implementing certain practices nor their effects. This approach greatly slows manufacturing improvement when lean practices are introduced on an ad-hoc basis. Without a fundamental understanding of key manufacturing principles, progress towards an optimal manufacturing paradigm will be highly iterative and subjective.

This thesis presents a systematic approach (based on Axiomatic Design [Suh, 1990]) for understanding the requirements and design implementations of a Lean Production System. This thesis defines the design attributes necessary to convert assembly and fabrication systems that were fashioned with a craft and job shop mentality to a system that espouses and uses the principles of lean manufacturing. The hypothesis is that a set of lean production design attributes applies to both the automotive and other lower volume industries like aircraft. The thesis is based on six different company studies: two automotive companies (lean versus mass producer), three aircraft engine companies, and one OEM company. From the lessons learned in the case comparisons, a methodology for designing new production systems or converting existing ones to a production system that utilize the lean production system design attributes will be presented in this thesis.

1.2 Changing the economic justification from 'scale' to 'time'

Before starting with the core of the thesis, it is necessary to point out that one of the primary differences between mass production and lean manufacturing is the shift in focus of manufacturing from economies of scale to "economies of time". Mass producers depend primarily on two things, economies of scale and specialization. Workers need to get more and more specialized in order to do their jobs more efficiently. And factories need to get bigger and bigger to achieve the economies of scale. However this entails the cost of inability to respond to rapid changes in demand due to heavy costs of changing the production line and an unacceptably high rate of faulty products due to large batches that make it difficult to detect defects.

On the other hand, lean manufacturing focuses all their energies on "time". Time is the heartbeat of the manufacturing system (Takt time), it controls the material in the system (Kanban is based on lead time and time frequency) and time is used to define the design of the machines and operations. In the chapters to follow it will be seen that the "time variable" is the most critical parameter considered in the design of lean production systems.

1.3 Product Complexity or System Design?

Figure 1-1 shows two different steering gear housings. One is a single-piece aluminum cast, while the other housing is composed of three parts: rack housing, valve housing and cylinder tube. The housings are made at two different pants (Plant L and Plant M), which will be compared in Chapter 3. Plant M has eight times more inventory than Plant L with a lead time of 24 shifts at Plant M versus half a shift at Plant L and an internal scrap rate of almost 70 times more than Plant L. These data were collected for rack bar machining; however, it is comparable to rack bar housing machining. From Figure 1-1, which design is the one manufactured at Plant L, and which is the 'lean' company that has fewer inventories, lower scrap rates and less lead time?

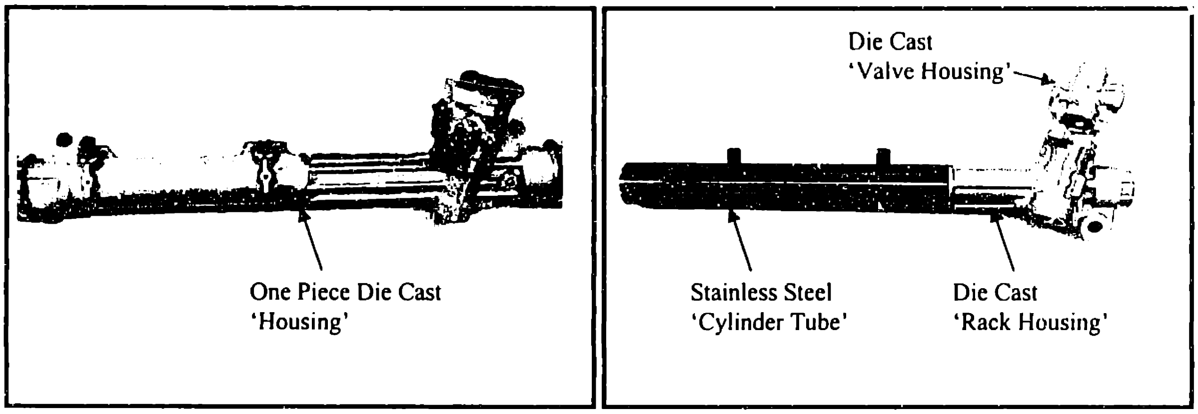


Figure 1-1: Differences in the Design of Steering Gear Housing from Two Automotive Plants

Most people have identified the figure on the left as being the one manufactured at Plant L; however, the steering gear produced at Plant L ("lean" plant) is on the right. Why do most people respond that the picture on the left is representative of the lean plant? It could be because of the guidelines developed by Boothroyd and Dewhurst for designing products. Those guidelines are called Design for Assembly (DFA) and Design for Manufacturing (DFM) [Boothroyd, 1992]. One of the rules under those guidelines states that a designer must "reduce the part count and part types" to maximize efficiency, minimize cycle times and reduce complexity during the manufacturing process. The argument is the fewer the parts in the product the easier it is to automate and the easier it is to control production because less parts in the product equates to less in-process inventory and less perturbations in the system (less suppliers and simpler logistics). Perhaps this argument makes sense; however, one should not conclude the argument is completely true. If the part count is reduced, time is taken from assembly and placed into machining. Combining several parts into one single part could create a more complicated part, making the tooling more complex, expensive and, machining time longer. Secondly, in many instances, it takes less time to assemble a product than to machine a part. Also by having more standard simpler parts, more combinations could be made to produce different products when assembled together [Whitney, 1996]. Assembling a larger quantity of simpler parts presents its own problems, mainly logistic in nature, but this problem can be solved by designing a manufacturing system to handle such situations. Can we then argue then that it is the system design and not product complexity that is correlated to the throughput time, inventory, scrap rates, and others?

1.3.1 Aircraft Engine Study

Three aerospace companies (A, B and C) from the engine sector of the Lean Aerospace Initiative were visited, studied and analyzed to understand the causes of throughput delay in the aircraft engine assembly. At the same time, the companies were studied to understand the applicability of lean manufacturing outside the automotive industry in cases where production is low in volume and high in model variety (i.e. aircraft manufacturing).

Both military and commercial engines were studied in the three companies visited. All engines studied were similar in thrust and size. Although the external design was very similar, the part count varied from engine to engine. A correlation was identified between the part count and planned time to assemble. When the study was completed we found that the engines with the highest part count (Company C) were the ones with more predictable and stable output, while the engines with less part count were very unpredictable in the throughput time (Figure 1-2).

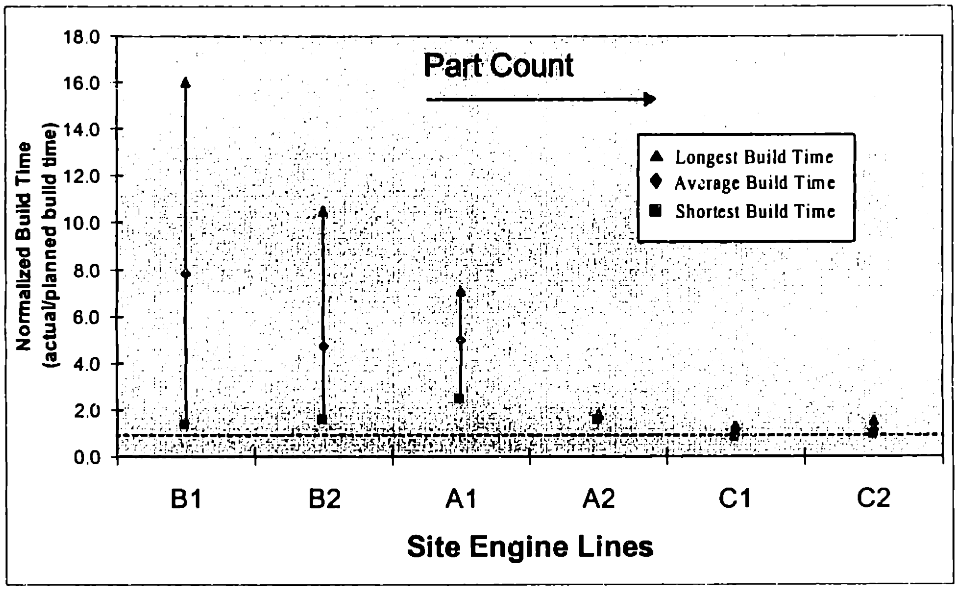


Figure 1-2: Build Time Variability from Three Aircraft Engine Companies

From the study it was also observed that the primary cause for delay and variability in build time was part shortage. For companies in the engine sector, defining part shortages as the number one reason for delay made sense because trying to assemble a product with as many as 30,000 parts is a very difficult task. At Company A, 38% of the time deviation from planned build time could be attributed to part shortages, while at Company B this time was 70%. On the other hand, at Company C part shortages were not a problem because 97% of the time parts were 'on-hand'. Company C has also eleven yearly inventory-turns, which means that its inventory storage is relatively small (inventory turns at Company B are 2-3 times per year). Company C was also the only company that designed its assembly line to produce at the customer demand rate, implemented a kanban system to control material and created a predictable output. In other words, Company C designed its production system to be one that can handle problems that a 'complex' product may cause.

The case study in the automotive industry and the findings from the aircraft engine sector could reach the conclusion that it is the system design and not product complexity what is correlated with throughput time and predictable output. In chapters four to eight, Plants L and M, and Companies A, B and C will be compared against the different lean concepts that allow a system to achieve the highest benefits in productivity gains.

1.4 Outline of Thesis

This thesis is consists of three main sections. The first section comprises Chapters 1 though 2. Chapter 1 provides some background and motivation to the development of a structure framework and methodology to understand and implement the design attributes of a lean production system. Chapter 2 compares two Plants (L and M) in terms of investment, throughput time, quality, direct and indirect labor, and customer responsiveness. Both Plants manufacture the same product under different production systems. Plant L produces its product on lean manufacturing cells, while Plant M has a traditional batch-mass production system.

The second section includes Chapters 3 through 7. The purpose of this section is twofold. First, identify and understand the design attributes that made Plant L superior to Plant M in terms of quality, inventory turns, productivity, throughput time and customer responsiveness.

Secondly, to demonstrate how these design attributes could be applied to the aircraft industry. Chapter 3 provides a description of The Production System Design Decomposition (PSDD) and Production System Hierarchy utilized to understand the design attributes of a Lean Production System. Chapter 3 gives also a small overview of how the framework was developed using the Axiomatic Design Concepts. Chapter 4, 5, 6, and 7 present the concepts of 'Balanced Production to Customer Demand', 'Leveled Production', 'Response Time < Demand Interval' and 'Predictable Time and Quality Output' respectively and how these concepts are applicable to the Automotive and Aircraft Industries. In each chapter, the Production System Hierarchy is used to analyze the lean production design attributes at the three different levels: 'Manufacturing System Design', 'Manufacturing Sub-System Design' and 'Machine/Operation Design'.

The third section includes Chapters 8 through 9. The purpose of this section is to develop an implementation methodology for Lean Production Systems based on the benefits and framework presented in previous chapters. Chapter 8 presents a methodology for designing new manufacturing systems or converting existing ones to systems that use the principles of lean manufacturing. In Chapter 9, the lean implementation methodology is used to convert an existing low volume/high mix company.

Finally, Chapter 10 provides a summary of this research and recommendations for future work. Appendix A presents a detailed explanation on how to create a standard work routine sheet, which is a tool very used in the creation and control of standard operations. Appendix B presents a glossary of terms frequently used in this thesis.

2

Manufacturing System Design: Mass versus Lean

2.1 Introduction

This chapter gives the first step in understanding the benefits of lean manufacturing and its differences from mass or batch production in the automotive industry. Two companies from the automotive industry (Plant L and Plant M) will be compared to understand some of the differences between "lean" and "mass" production.

2.2 Plant M versus Plant L

Plant L and Plant M produce power rack and pinion steering gears for automobiles. The rack and pinion steering gear is used indirectly by the driver to control the direction of the front wheels in the automobile (Figure 2-1). The rack and pinion steering gear is composed of many elements, such as the rack bar, pinion valve, housing, tie rods, and many other smaller parts. There are approximately 70 different part numbers in a rack and pinion steering gear.

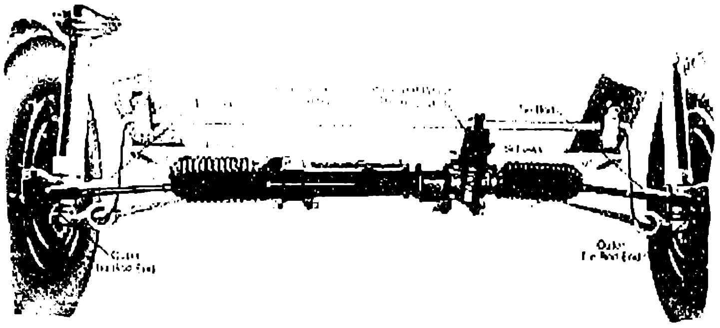


Figure 2-1: Rack and Pinion Steering Gear System

To make a comparable analysis of the fabrication systems at Plant L and Plant M, the rack bar (Figure 2-2) component, which is very similar in both plants, will be used as a basis of comparisons between both companies. The final assembly of the steering gear will be also analyzed in the subsequent sections. The machining and assembly at both plants will be compared in terms of floor space, labor requirements, capital investment, work-in-process inventory, quality (scrap rates) and flexibility in terms of product and volume.

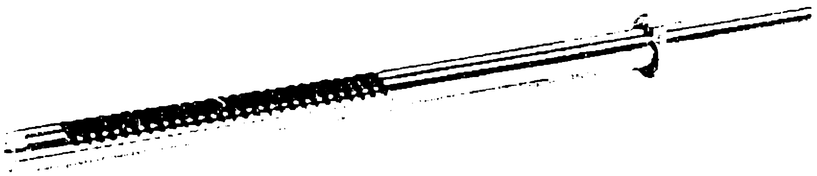


Figure 2-2: Typical Rack Bar Machined at Plant M and L

The manufacturing area at Plant M is 2,000,000 ft^2. Plant M is plant of on of the Big Three companies and currently produces approximately 11,000 steering gears per day for automotive assembly plants all over the world for its parent company. Plant M machines 5 parts for the steering gears: rack bar, housing, pinion, input shaft and torsion bar. Operators in Plant M are members of the United Auto Workers (UAW). Production at Plant M is controlled with an MRP system, and production is usually shipped to assembly plants once a week. The steering gears for Plant M were designed in the company's central headquarter location.. The design process is a traditional one, where designers are in another location (in this case almost 1,000 miles away) and once the design is completed it is passed "over the wall" [Clausing, 199] to the manufacturing site.

The manufacturing area at Plant L is 276,300 ft^2. Currently Plant L is producing around 5,000 steering gears per day distributed among seven different Japanese automotive assembly plants in North America. Plant L produces 4 parts for the steering gears, which are, rack bar, rack housing, valve housing, cylinder tube. Operators at Plant L are not members of any union. Plant L uses MRPII as a planning tool to determine a rough estimate of daily production and a pull system is used to more finely control the daily production in the factory. The products are shipped daily and one of the customers picks up finished goods every two hours. The product design process at Plant L is different from Plant M. The product design process starts with some overall requirements and specifications that the customers give to Plant L. Plant L's engineers carry out detailed design. In this manner, Plant L can more easily reuse existing machine designs or even existing machines that are no longer used. Plant L designs a steering gear that satisfies not only the requirements of the customer but at the same time satisfies the requirements and constraints of its manufacturing system.

2.2.1 Batch Flow Rack Bar Machining At Plant M

The machining of the rack bar is done in a traditional flow job-shop environment, where the layout of the machines is by processes but at the same time representing the flow of the part (Figure 2-3). Plant M starts by cutting the rack bar to the desired length from a long bar stock. After this process, the rack bar goes through other nine different processes. The rack bar is transferred from one process or machine to the other in batches of 600 parts in gons[•]. When the system was analyzed, there were 100,600 rack bars of work-in-process. A forklift truck is always needed to transfer the full gon from one machine to another. In some cases, there are intermediate storage places for overproduction. Currently it takes 10,700 minutes, equal to almost 24 shifts of production, for a rack bar to go from start to finish.

[•] A gon is large steel bucket (3' long x 2' wide x 3' tall) used to transfer parts from machine to machine.

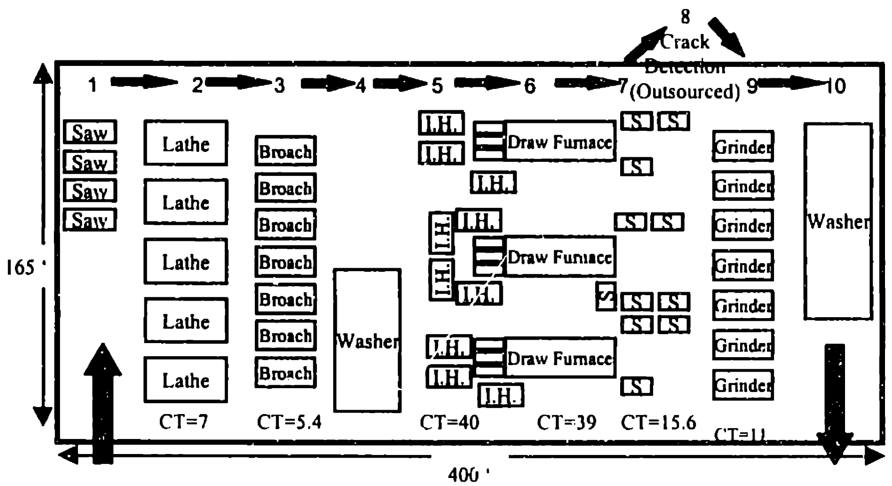


Figure 2-3: Rach bar Machining area [Charles 97]

The rack bar machining area is 66,000 ft^2. There are 49 machines with a capital investment of $29.5 Million. Most of the equipment is 10-20 years old. From Figure 2-4, it can be seen that the average machine cycle time varies from 5 to 40 seconds. The Washers were excluded from the figure below because cycle time was very unpredictable.

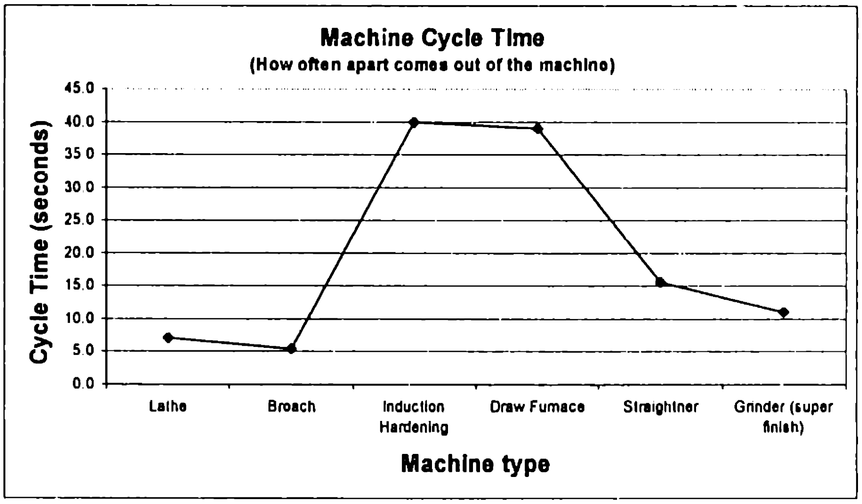


Figure 2-4: Machine Cycle Time Variability in Rack Bar Machining at Plant M

The total number of operators needed to maintain the system running is 28 (Table 2-1). Every day the rack bar machining area runs approximately one hour extra of overtime for 20 operators, which translates into 20 hours of overtime cost (one hour for every operator). An operator inspects one rack bar every time a batch of 600 is produced or when a changeover occurs. The only standard inspections done on the rack bar are during crack detection (outsourced) and during the straightening operation.

Resource Requirements	
No. of Direct Workers	18.00
Supervisor	1.00
Reliever	0.00
Job Setter	3.00
Repair Defective	0.00
Maintenance	3.00
Scheduling	1.00
Material Handler	2.00
Total Workers	28.00

Table 2-1: Labor Requirements in Rack Bar Machining at Plant M

2.2.2 Cellular Rack Bar Machining at Plant L

The machining of the rack bar at Plant L is done in a cellular environment, where the machines have product oriented layout (U shape layout) (Figure 2-5). Plant L receives incoming bar cut-to-length from suppliers. There are 21 different processes in the cell designed at Plant L. Most of the time two or three operators are running the cells. The operators move the rack bar from one machine to the other. When the operator unloads the part from one machine and transfers it to the next machine, he can verify visually that there are no scratches, marks or any other defective characteristics. In some instances, the operator even places the part in a gage to quickly perform a quality check. The throughput time of a rack bar (time it takes a rack bar to go through the 21 processes) is 70 minutes. Finish rack bars are transferred from machining to assembly in a roller cart.

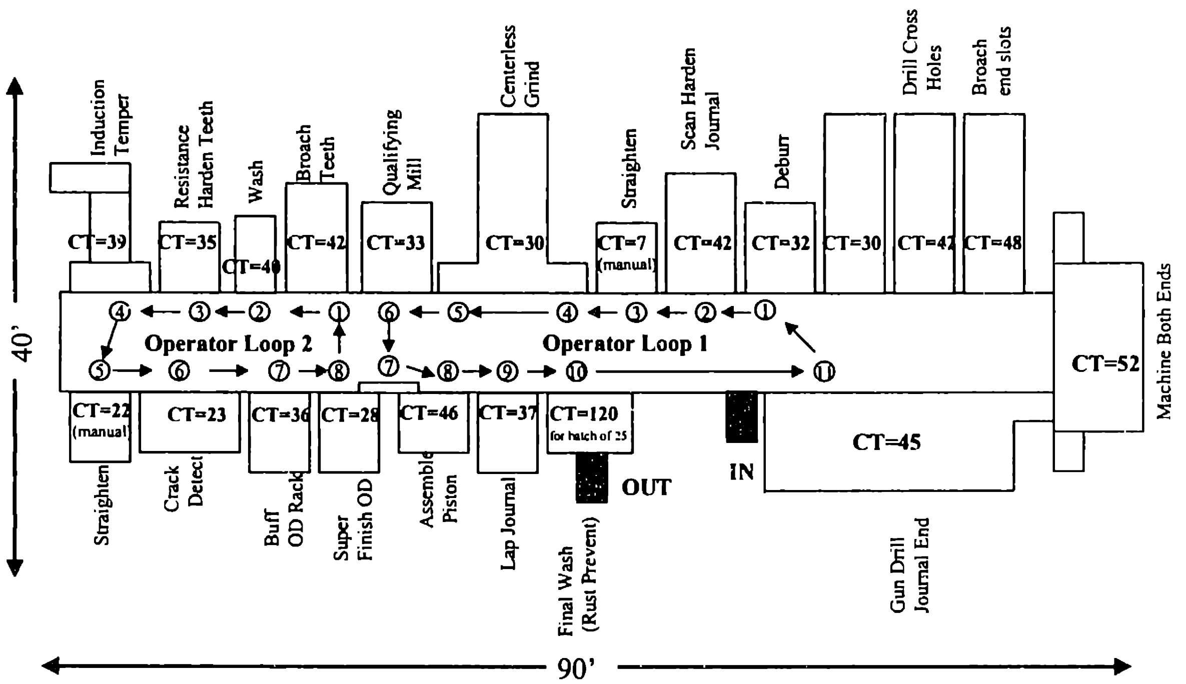


Figure 2-5: Cellular rack bar machining

The rack bar cell area is 3,600 ft^2 and most of the equipment and machines in this cell are 10-20 years old. The machining cell requires a total of four (Table 2-2) workers to keep the line running. Two operators are needed full time to run the cell and two other operators can perform the different tasks in Table 2-2.

Resource Requirements	
No. of Direct Workers	2.20
Supervisor	0.20
Reliever	0.20
Job Setter	0.20
Repair Defective	0.20
Maintenance	0.40
Scheduling	0.00
Material Handler	0.50
Total Workers	3.90

Table 2-2: Labor Requirements for Cellular Rack Bar Machinig

The cycle time from machine to machine is very consistent. The average machine cycle time is 39 seconds with a maximum deviation of ±3.5 seconds (Figure 2-6). The consistency and small variation in cycle time from machine to machine eliminates inventory in the system and creates a more predictable output by making problems more visible. From Figure 2-6, one can argue that machines at Plant L were designed for a specific range of time in order to minimize investment, cost of inventory, create a predictable-synchronous output and other requirements depicted at the system's level. The chapter on Balanced Production explains in greater detail the concept of designing machines for ranges of "takt time". Manual operations, like straightner and crack detect, were eliminated from Figure 2-6 to compare only machine cycle times against Plant M's machines.

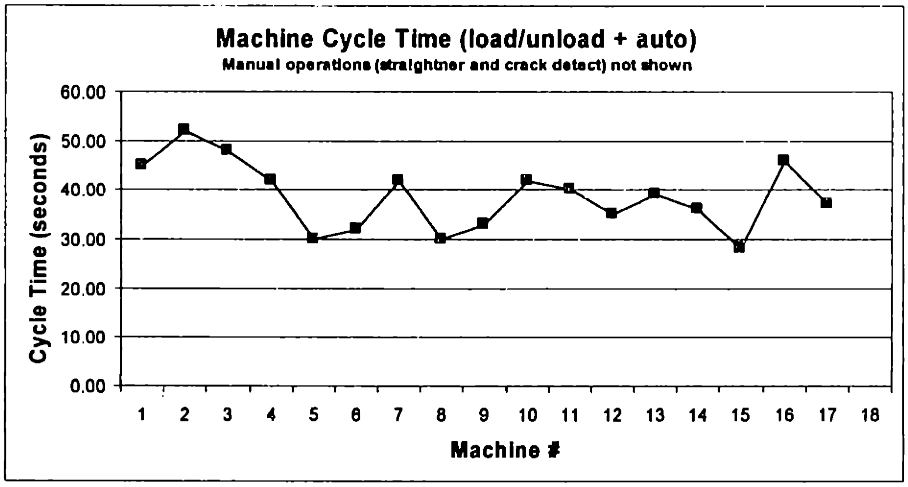


Figure 2-6: Machine Cycle Time Variability in Rack Bar Machining at Plant L

2.2.3 Benefits of lean cells versus mass production flow shops in rack bar machining

The data obtained from both plants was normalized with respect to the production rate at Plant M and then plotted in Figures 3-7a and 3-7b. The normalization factor was 8.5, which means that 8.5 rack bar machining cells at Plant L are needed for the same production rate as in Plant M.

Great variability in cycle time from one machine to another and high 'machine utilization' without consideration to customer demand rate, creates the need for high levels of work-in-process inventory (WIP) and longer lead times. The WIP within the machining system at Plant M, was found to be almost 80 times that of Plant L. At the same time, lead time is 45 times greater in Plant M than in Plant L and correspondingly the scrap rate is 70 times higher (Figure 2-7a).

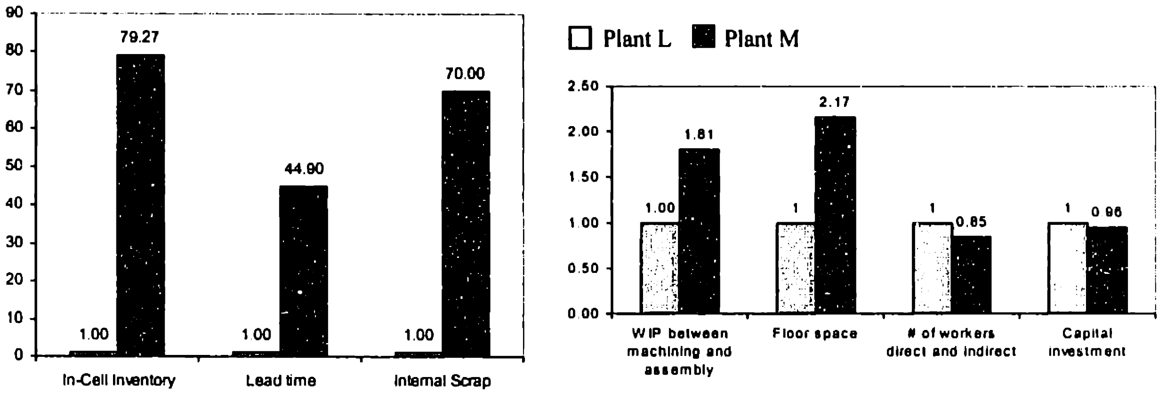


Figure 2-7a and 2-7b: Normalized results (with respect to production rate) from Plant L and Plant M Rack Bar Machining Comparison

From Figure 2-7b, it can be seen that for almost the same capital investment, Plant M needs more than twice the floor space when compared to Plant L. The number of workers is very similar when comparing both companies; however, the inventory of finish rack bars (WIP between machining and assembly) is almost twice as much in the batch flow shop.

2.2.4 Non-Synchronous Transfer Line Assembly System at Plant M

The assembly of the steering gears at Plant M is done in a transfer line (Figure 2-8). The operator is tied to one station waiting for the part to stop at his/her station in order to perform the operations. Every station was designed to run at a 10 second cycle time. When an automatic machine exceeded this cycle time, more machines would be bought and run in parallel to achieve the 10 second cycle time. At time of the study there were 38 stations in the assembly line.

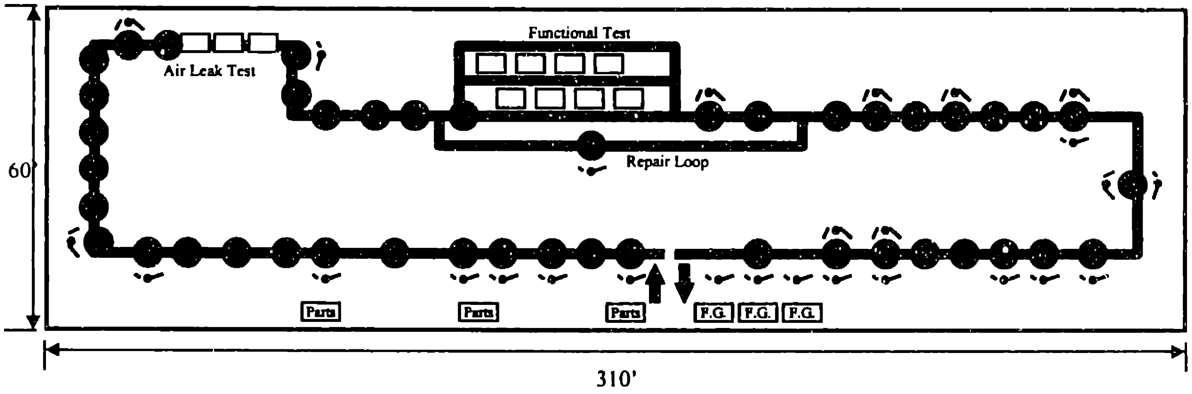


Figure 2-8: Assembly Transfer Line at Plant M [Charles 97]

The assembly line needs 45 people to keep the line running. The subdivision of labor is shown in Table 2-3. Plant M has a dedicated crew to setup the line and prepare the equipment for assembly. Since absenteeism is very high, Plant M has a dedicated crew to cover for the people absent. This illustrates the inflexibility and dependence on people of the line. If there are not enough workers to cover all the stations, then the line can run. In sharp contrast, at Plant L, if an operator or two are absent, then the line can still be run by increasing the work loops. At Plant M, three full time workers repair steering gears that were rejected by functional test.

Resource Requirements	
No. of Direct Workers	30.67
Supervisor	1.00
Reliever	5.00
Job Setter	4.00
Repair Defective	3.00
Maintenance	0.67
Scheduling	0.17
Material Handler	0.67
Total Workers	45.17

Table 2-3: Labor Requirements in Steering Gear Assembly at Plant M

2.2.5 Cellular Assembly System at Plant L

The assembly of steering gears at Plant L is done in a cellular assembly line (Figure 2-9). The operator moves from station to station performing different operations. Each work-loop seen in Figure 2-9 needs to be performed in less than the Takt time, which in this case is approximately 75 seconds. Every operation is done serially, meaning every part goes through every station.

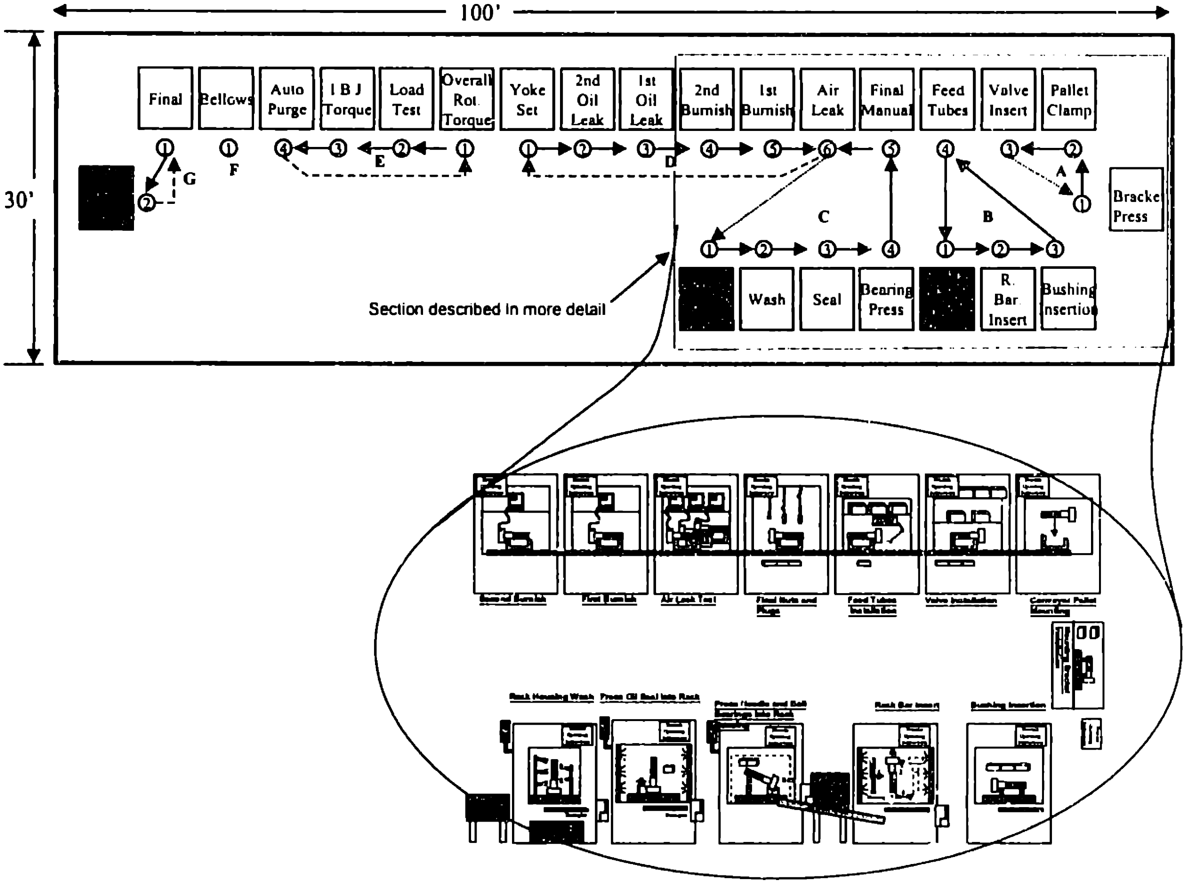


Figure 2-9: Assembly Cell at Plant L

The assembly line needs 9 workers to run the line (Table 2-4). The team leader is responsible for repairing any defective parts made or for finding the root cause of the problem and also acts as the supervisor of the line. The team leader, in conjunction with the operators are in charge of performing setups or chageovers; however, the team leader is in charge of inspecting all pokayokes and gages in the machines at the beginning and end of the shift. If any worker needs to take an extra break, (i e. go to the restroom) or if an operator is absent, the team leader relieves his/her position on the line. The main principle here is empowerment of the workforce.

Resource Requirements		
No. of Direct Workers	7.50	
Supervisor	0.25	Team Leader
Reliever	0.25	
Job Setter	0.25	
Repair Defective	0.25	
Maintenance	0.33	
Scheduling	0.00	
Material Handler	0.50	
Total Workers	9.33	

Table 2-4: Labor Requirements in Steering Gear Assembly at Plant L

2.2.6 Benefits of Using Lean Cells versus Transfer Lines in Steering Gear Assembly

The data for the assembly systems was normalized with respect to the production rate at Plant M. In this case, the normalization factor was 5.4, which means that 5.4 cells at Plant L are needed for the same production rate as in Plant M.

The next figure shows that Plant M has 8 times more warranty problems that Plant L. Warranty problems are problems detected by the end user or driver of the vehicle. Customer satisfaction is extremely important because once the customer is disappointed, it is very difficult to gain his trust and confidence back. It is by far more efficient to retain customers than trying to win back dissatisfied customers or acquire new customers [Ettlie, 1998]. Line returns or returns from the vehicle assembly plants at Plant M are 1.4 times higher than in Plant L; meaning that the assembly plants with higher defects or line returns would have more perturbations in the system thereby creating higher variability in the throughput time. For this reason we see that the Plant M has twice the in-line inventory and almost 2.5 times more finish goods inventory.

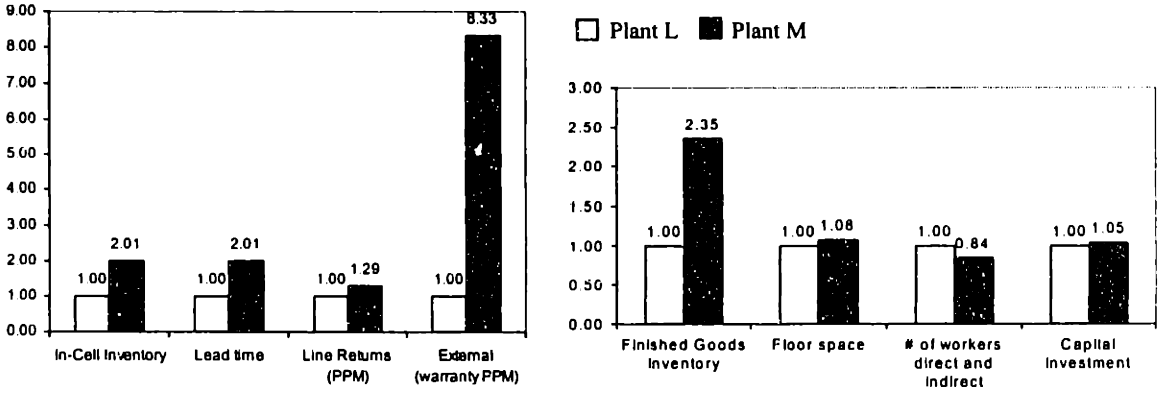


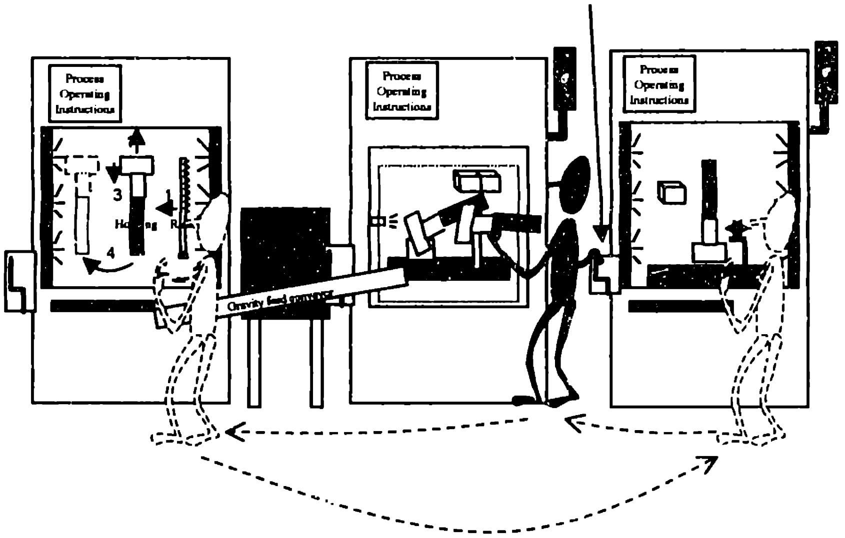
Figure 2-10a and 2-10b: Normalized results (with respect to production rate) from Plant L and Plant M in Steering Gear Assembly Comparison

One of the most important features of the assembly cell at Plant L is the ability to have the workers move from one station to another. To achieve movement of workers, the stations need to be designed in such a manner that the separation of the worker from the machine can be achieved (Figure 2-12). The separation of the worker from the machine should not be confused with completely automating the stations. The separation of the worker from the machine tries to create the most efficient interface between the worker and station. The goal is to have the worker perform the complex, non-linear motions such as, load the part or parts into the machine, while the machinery performs some activitites automatically with linear motions to increase accuracy and help the worker in his/her tasks in a reliable manner. Not only loading the part manually is faster, but also more accurate because the operator uses the "human sensors" (touch, vision, etc) to determine if the part has been located correctly and can also perform a visual quality check on the part. The separation of the worker from machine also helps to balance the production line by adding or removing the workers. The concept of semi-automating the operations (load/unload manual while automatic processing) to separate the worker from the machine is called 'jidoka' [Schonberger, 1982]. From the Table 2-11, it can be seen that one third of the stations in the assembly line at Plant L are semi-automated and are using the concept of Jidoka. The testing machines at Plant L are the automatic stations. These stations were automated because the operator does not need to make any visual chaeck on the product. On the other hand, we can see that Plant M is using either automatic or manual stations, and does not integrate the worker with the machine by using jidoka.

	Plant M	Plant L
Manual Stations	21	8
Semi-Automated Stations	0	7
Automatic Stations	21	7
Total	42	22

Figure 2-11: Use of Jidoka in Assembly at Plant L versus Plant M

Using the concept of Jidoka in assembly and machining achieves not only separation of worker from the machine, but also helps to design a lower cost, simpler and more reliable machine, with only linear motions. Jidoka is also meant to give machines and equipment "human-like intelligence" by adding defect prevention/detection devices (poka-yokes).



"Walking switch"
worker hits the walking
switch when moving from
one machine to another
to start the machine cycle

Figure 2-12: Implementing Jidoka to achieve Man-Machine Sepration

3 The Design Decomposition Framework

3.1 Introduction

This chapter introduces the lean Production System Design Decomposition (PSDD) [Cochran et al., 1998], which is the framework used in Chapters 4 though 7 to understand the applicability of the lean manufacturing design attributes in the aircraft and automotive industries. This chapter also introduces the essential concepts of Axiomatic Design, which is the design structure used to develop the PSDD framework.

3.2 Key Concepts of Axiomatic Design

Axiomatic Design defines design as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through mapping between Functional Requirements (FRs) and Design Parameters (DPs) [Suh,1990]. The FRs represent the goals of the design or *what* we want to achieve. FRs are defined in the functional domain in order to satisfy the needs which are defined in the customer domain. The DPs express how to satisfy the FRs. DPs are created in the physical domain to satisfy the FRs. The design domains are shown in Figure 3. The customer domain is where the customer needs reside. These needs must be mapped to the functional domain where the customer needs are translated into a set of FRs, which by definition, are independent. Not only will Functional Requirements be defined for the new design, but also constraints will appear as a result of translating customer wants into FRs. Constraints have to be obeyed during the entire design process. They refer to FRs, as well as to DPs. This fact is indicated in Figure 3-1 by placing the constraints above the functional, physical and process domain. The FRs are then mapped to the physical domain and the DPs are mapped to the process domain in terms of process variables (PVs).

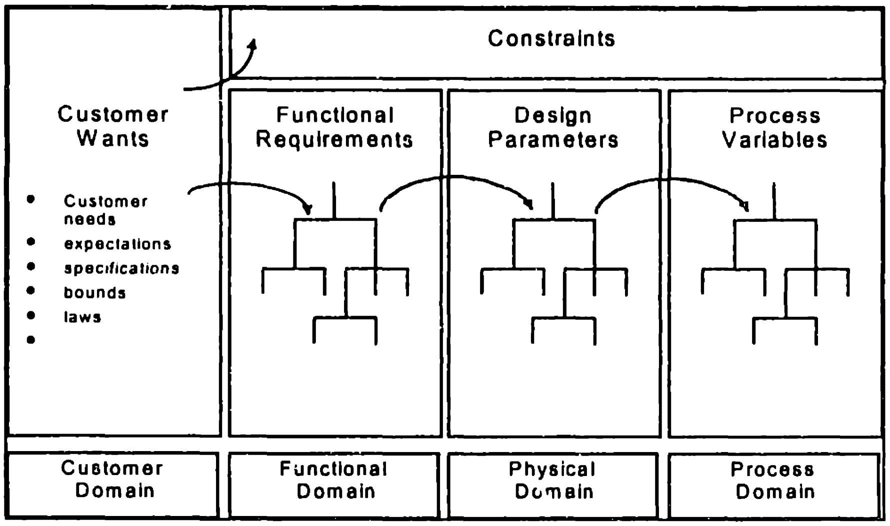


Figure 3-1: All Designs can be Represented in Four Domains [Suh,1990]

In most design tasks, it is necessary to decompose the problem. Figure 3-1 indicates hierarchies in the functional, physical and process domains. The authors believe that in the case of a manufacturing system design, the decomposition in the Functional Domain and Physical Domain is most effective. Zigzagging between the domains yields the development of the hierarchy. The zigzagging takes place between two domains. After defining the FR of the top level, a design concept has to be generated. This results in the mapping process as shown in Figure 3-2

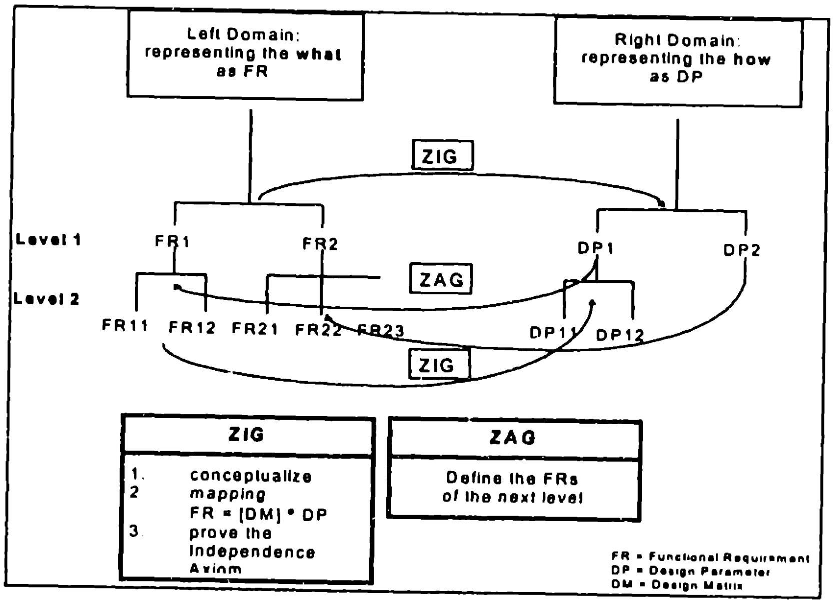


Figure 3-2: Zigzagging Between the Domains to Developed the Hierarchy

In order for mapping to be satisfied between domains, two axioms must be followed [Suh,1990]:

Axiom 1: *The Independence Axiom*

Maintain the Independence of the FRs

Axiom 2: *The Information Axiom*

Minimize the Information Content of the design

3.3 Lean Production System Design Decomposition

The two tenets of Axiomatic Design that are the foundation for developing The Production System Design Decomposition (PSDD) are the Independence Axiom and the idea that any design must be decomposed into its constituents levels by 'zig-zagging'. The functional requirements (FRs) and design parameters (DPs) of a production system are shown in the decomposition developed by Dr. David Cochran, Dr. Paulo Lima and students of the Production System design Laboratory at MIT. The Production System Design Decomposition (PSDD) is a tool that can be used to study and learn more about lean production systems, specifically to understand more the relationship that exists from *what* a Lean Production System wants to achieve and *how* it is achieved.

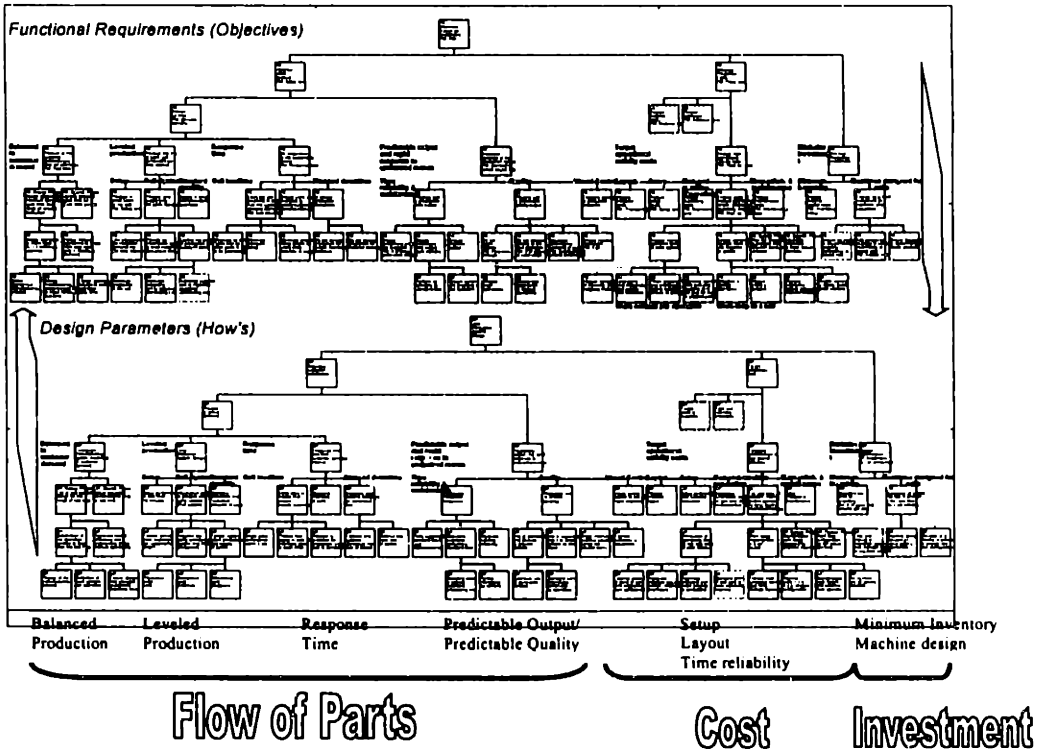


Figure 3-3: Production System Design Decomposition

The Production System Design Decomposition presented in Figure 3-3 can be subdivided into three major groups, which are: flow of parts, cost and investment. The flow of parts depends

- Balanced production to customer demand
    - Cell design to achieve range of demand
    - Man-Machine separation
    - Machines designed for cells
- Leveled Production
    - Set up Reduction
    - Pull System
- Response Time < Customer Demand Interval
    - Cell Lead Time
- Predictable output and rapid response to undesired events
    - Time reliability and maintenance
    - Quality

  - Visual Control

The other two groups that the PSD Decomposition describe, are:

- Target operational activity costs
  - Layout
  - Setup
  - Man and machine separation
  - Time reliability and maintenance
- Minimize investment
  - Minimum inventory
  - Machines designed for cells

The focus of this thesis is in the groups that comprise flow of parts rather than cost and investment. Cost and investment can be consider to be constraints more than requirements or design attributes of a production system. Reducing cost and minimizing investment are results of the system implemented and in many instances, the results from continuously improve the production system. Future research needs to be done in the area of cost and investment to quantify the cost accounting systems needed that can interact with the design of lean production systems. More industry examples and quantifiable analysis need to be done to prove the functional requirements and design parameters stated under the "cost" and "investment" groups.

3.4 System Architecture for analyzing a Production System

A production design hierarchy will be used in Chapters 4 through 7 to create a systematic approach to the description and analysis of each of the groups mentioned the previous section. This systematic approach will help in the creation of the methodology that will be developed in later chapters. Figure 3-4 shows that the production design hierarchy is composed of a Manufacturing System Design level followed by a Sub-System or Cell Design level and then the Machine/Operation Design level.

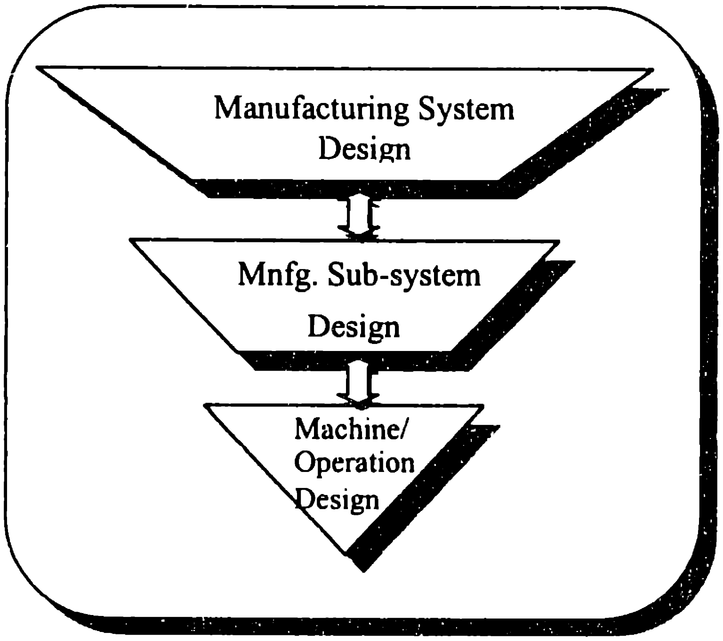


Figure 3-4: Production System Design Hierarchy

In engineering, we are always taught that in order to solve any problem the first step is to define the system and its boundaries. If the boundaries of the system are wrongly chosen, then heat, work or energy will be transferred in the wrong direction giving an erroneous answer. In the same manner, before designing a production system, we have to first define what we mean by production system and then determine the boundaries of those systems.

The word *system* is used to define "a collection of elements aggregated by virtue of the links to form, process, or function which tie them together and cause them to interact" [Rubeinstein, 1975]. Consequently, a *manufacturing system* can be defined as a network of processes, operations and information flow (Figure 3-5). A process is the transformation of material into product and this transformation is accomplished through a series of operations. Information flow is required to initiate and assist both process and operation [Shingo]. A production system includes all the necessary activities to achieve consumer needs that are sold on the market. These consumer needs can be either a product, a service, or combination of both.

The manufacturing sub-system is the collection or arrangement of operations and processes used to make a desired product (s) or component (s) [Black,1991]. The manufacturing sub-system includes the actual equipment composing the processes and the arrangement of those processes. Examples are a job shop, a Flexible Manufacturing System (FMS). Inside this sub-system, another level of decomposition can be categorized, which is the machine/operation level.

The *machine/operation* level is composed of the individual operations inside the entire manufacturing process. This level takes a closer look at the design of the machines/stations that are in the system. The operations will be designed individually but since the requirements of the system cascaded down from the first and second level, the operations will be designed to meet the requirements of the entire system.

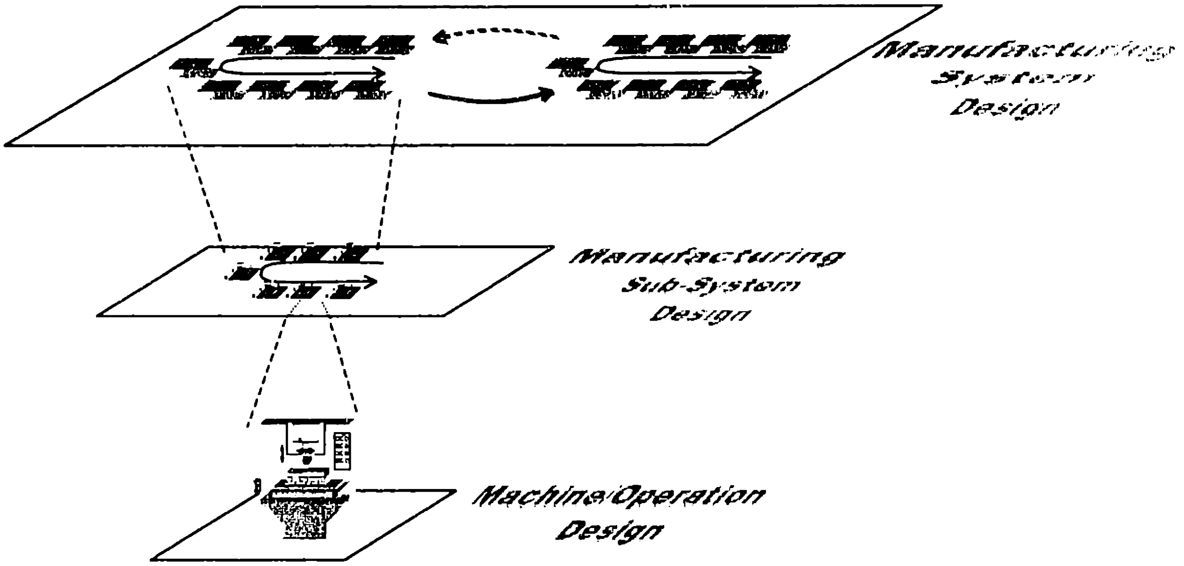


Figure 3-5: Boundaries of the Production System Design Hierarchy

4 Balanced Production

4.1 Focus on Takt Time[+]

Balanced production occurs when all operations or cells produce at the same cycle time that is equal or less than the takt time or customer demand cycle time. In other words, balanced production means to produce at the "right rate", which is the rate imposed by the customer. The customer in this situation can be final assembly, a subsequent process or even the end user of the product.

The most important enabler to achieve balanced production is to design the cell or sub-system to meet a range of takt times. In many cases to meet the lower end of the takt time range must be done by subdividing the operations of a manufacturing process. Some of the benefits obtained by implementing the design parameters of a balanced system are less inventory of finished goods and work-in-process, on-time delivery and effective use of capital investments.

[+] Takt Time = available time in a day ÷ average daily demand

4.2 Manufacturing System Design

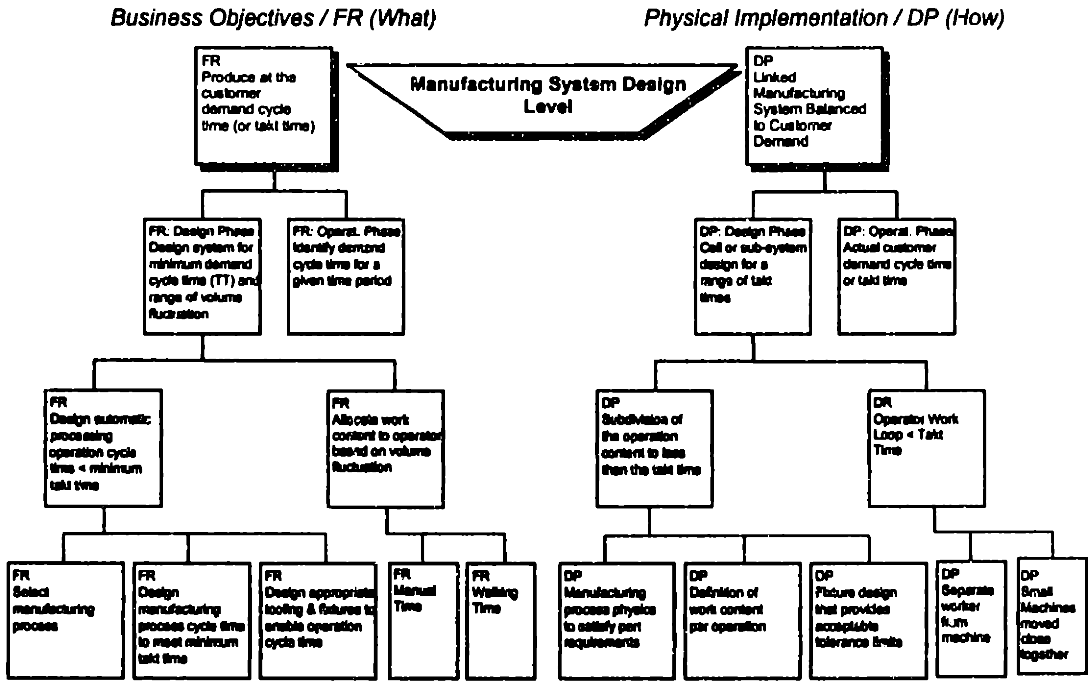


Figure 4-1: Decomposing the requirements and design parameters of the manufactuiing system level for a linked-balanced production system

4.2.1 Automotive Industry

At the manufacturing system level, balanced production tries to "link" each element of the manufacturing chain to the customer demand cycle time or takt time. These elements are assembly, sub-assembly, fabrication, suppliers and customers. A balanced system tries to unify the supply chain by making all the production cells and suppliers produce at the customer demand cycle time. In the automotive industry, if the final assembly of a car runs at a cycle time of 75 seconds, then in order for a plant to be balanced with the customer demand cycle time should produce at a demand cycle time of 75 seconds per part.

Two plants are compared, Plant M and Plant L. Plant M was never designed with the idea of balancing the production with the customer demand cycle time. Plant M was designed with the idea of aggregating as much demand as possible into one assembly line or machine to get the gains from the economies of scale and to fulfill a vehicle program's total or aggregate requirements.

Figure 4-2 demonstrates that the average cycle time from the 'batch flow shop' (6.3 sec) in Plant M is almost the same as the cycle time in assembly (10 sec). However, when analyzing the cycle time of each machine in the rack-bar machining area, it was found that the machine cycle times ranges from 5 minutes to 40 minutes. Due to this variability in cycle time, the work-in-process (WIP) inventory is 80 times higher when it is compared with the balanced system at Plant L (Figure 2-7). Because of fast cycle time in the rack-bar machining area and because of the "machine utilization" performance measure used at this company, the workers are always tied to one machine or a group of machines.

The assembly transfer line is producing one steering gear every 10 seconds, while one of the customers is demanding a steering gear every 75 seconds. Since producing steering gears for one customer will not be cost effective in the way that the assembly line was designed, the demand of two other plants was aggregated to this line. Aggregating that much demand into one line is well justified with the "economies of scale" principle (make more to decrease the unit cost). Nevertheless, when aggregating that much demand into one assembly line makes the line run at a very fast rate, which then requires having one worker tied to one station. This means that when demand goes down, the workers will still be doing the same amount of work yet at a slower rate. This inherent inflexibility of resource allocation is then translated into cost of overproduction ("just in case" manufacturing) and cost of un-utilized labor and equipment.

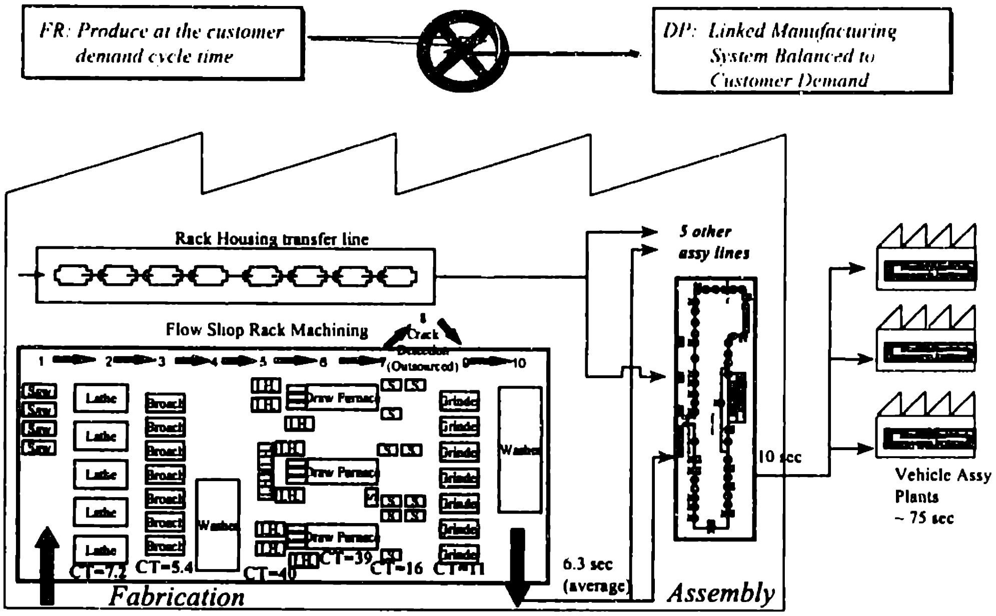


Figure 4-2: Manufacturing system design at Plant M

On the other hand, Plant L designed assembly cells to produce at the customer's demand cycle time. If the demand rate changes, Plant L can easily modify their production rate to be balanced to the customer demand rate by adding or removing workers. These cells can make an average of five different models per cell and most of the time are producing for one "customer" or assembly plant.

Figure 4-3 demonstrates how Plant L is running production to be balanced to the customer demand cycle time. The machining area is producing at a lower cycle time because it is balanced to the spare parts business and new steering gear business. Another reason for running at a slower cycle time is due to the setup time and machine downtimes, which are higher in machining than assembly.

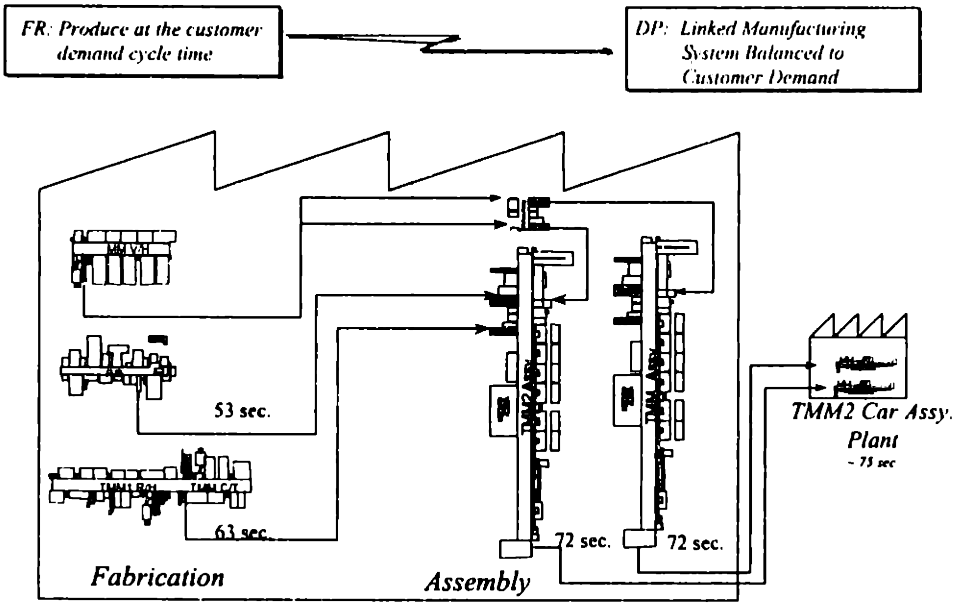


Figure 4-3: Manufacturing System Design at Plant L

4.2.2 Aircraft Industry

Balanced production in the aircraft industry means the same as in the automotive industry. That is, to have all operations and lines produce at the same cycle time of the customer's demand cycle time or takt time. The primary difference is the units of time and sometimes the size of the part. In the automotive industry, cycle times are in seconds because of high volume (~ 300,000 cars/year per model type), while in the engine aircraft industry cycle times are in hours due to smaller demand volumes (~ 150-300 engines/year for an engine model type).

In many instances, the dynamics in the aircraft industry creates an easier environment for applying some lean manufacturing techniques. Most of the time, orders in the aircraft industry are placed in large quantities that need to be delivered over a long period of time (usually at least a year). The main component of demand variability in the aircraft engine industry comes most of the time from differences in year-to-year order levels compared to daily or weekly demand changes in the automotive industry. Since the demand is very stable over a year, the takt time could be used for designing a production line and to balance it with customer demand.

From the aircraft engine study, it was found that implementing a linked manufacturing system balanced to customer demand helped achieve great gains in production efficiency at Company C. Company C applied, among others, the concept of balanced production to customer demand and achieved a 100% on-time delivery to their customers. This customer demand takt time was also deployed to the sub-assemblies feeding the final assembly, just like Plant L. There are some sub-assemblies producing at a faster cycle times because spare sub-assemblies are produced in those stations as well. Figure 4-4 shows the physical implementation of an aircraft engine company after implementing the concepts of balanced production. The more fundamental requirements and design parameters needed to achieve the goal of balanced will be explained in the next sections.

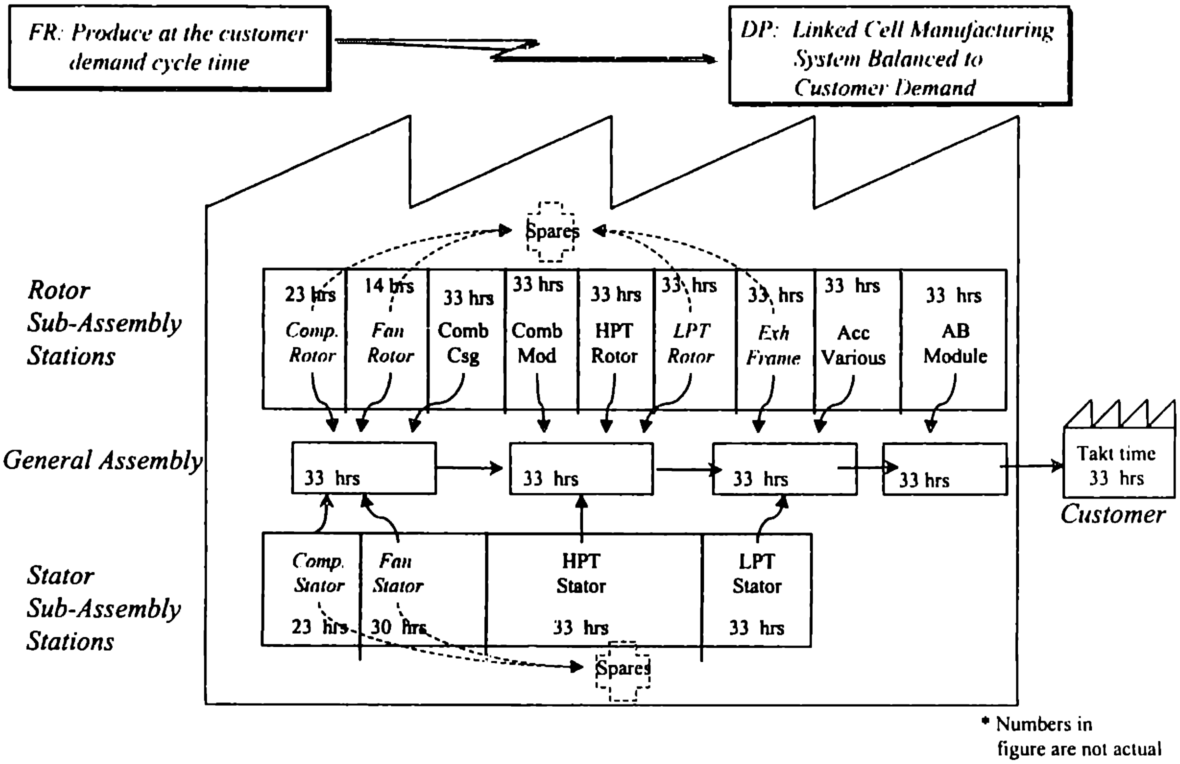


Figure 4-4: Linked Manufacturing System Balanced to Customer Demand

4.3 Manufacturing Sub-System Design

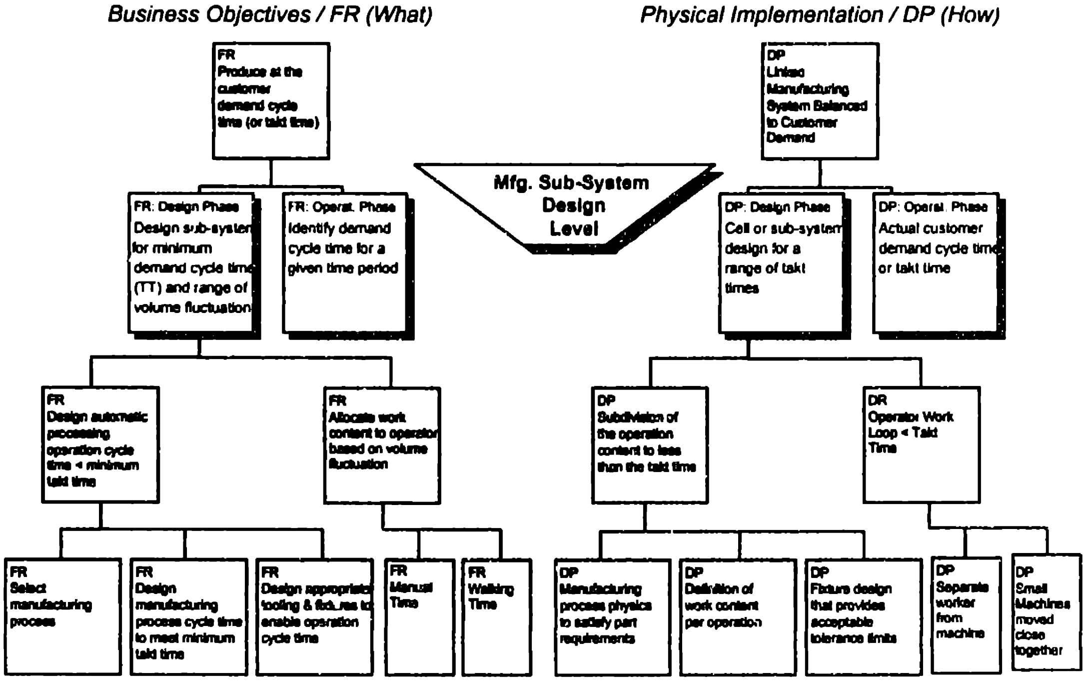


Figure 4-5: Decomposing the requirements and design parameters of the manufacturing sub-system level for a linked-balanced production system

Customer demand cycle time is very dependent on market performance and economical stability. It is for this reason that the biggest problem in designing a manufacturing system deals with the unpredictability of forecasted demand. Forecasts have been found to be always wrong and very unreliable [De Neufville, 1997]. No matter how much effort is imposed on studying the market and obtaining better customer orders predictability, it will never be the same as actual demand. This unpredictability is present in the automotive industry as well as in the aircraft industry. The traditional way of thinking is to minimize the uncertainty inherent in forecasted numbers by designing better tools and to design a manufacturing system with "extra" flexibility (in many cases completely automated) to eliminate and absorb demand uncertainty and variation. The new mentality and solution to the unpredictability of demand is to have an optimal flexible sub-system that can adapt quickly to the changes in actual demand. Since flexibility is difficult to measure and quantify in terms of cost, efficiency and performance, the sub-system should be flexible enough to operate efficiently over a range of operating conditions. That is, the sub-system is designed for a minimum takt time and operated by the actual customer demand takt time, which could vary from one time period to another. This range in capacity is based on the unpredictability of demand and the takt time.

4.3.1 Automotive Industry

In Plant M, a new production line is designed based on 'one number', which is the highest forecast demand number across the product life cycle (Figure 4-6). When demand goes down, the line is either shut down for some amount of time or parts are just produced for inventory.

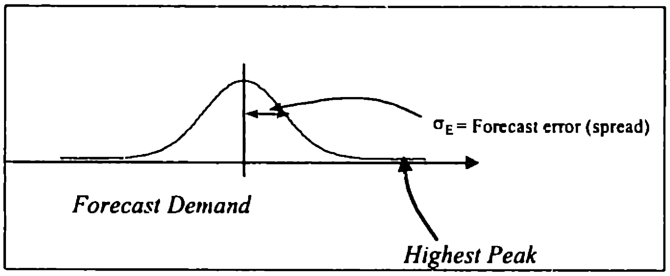


Figure 4-6: Traditionally lines Designed to Achieve a specific Production Rate

On the other hand, the lines at Plant L are designed to meet a range of demand levels. The forecasted demand, which can be represented with a normal distribution, is then translated into a uniform distribution signifying that the system should respond to a range of operating conditions (figure 4-7)[Cochran, Reynal 1997]. At Plant L, it was decided that the lower end of the uniform distribution or the minimum takt time would be in the range of 40 seconds. This lower end of 40 seconds (highest capacity requirement), is chosen for assembly and fabrication lines in order to achieve flexibility of having operators perform tasks in work-loops, minimize investment of equipment by having less automation and achieve quality improvements. If the lower end is less than 40 seconds, more automation will be needed and the worker will either walk faster or the worker will start to work like the one in Plant M (one man, one machine). If demand continues to increase and takt time goes below 40 seconds in a 3-shift operation, then the company begins to think about replicating the cell

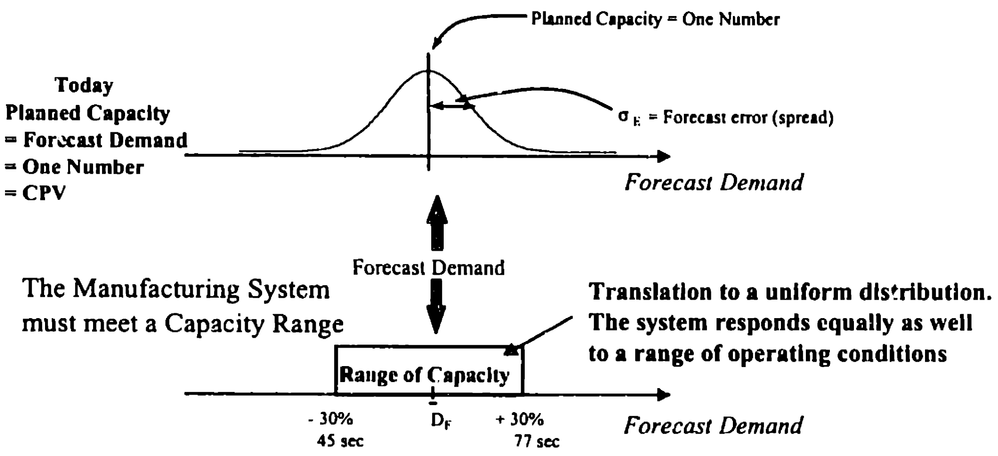


Figure 4-7: Design Manufacturing System for maximum demand cycle time and range of takt times

Once the cell is in operation, the range of capacity is achieved by adding or removing operators to/from the cell. Direct labor is between 5% to 15% (Figure 4-8) of the total cost of a product in the automotive industry. Therefore, using the workers to achieve small increments of capacity and meet the demand cycle time is more cost effective than adding capacity in big lumps by buying more equipment.

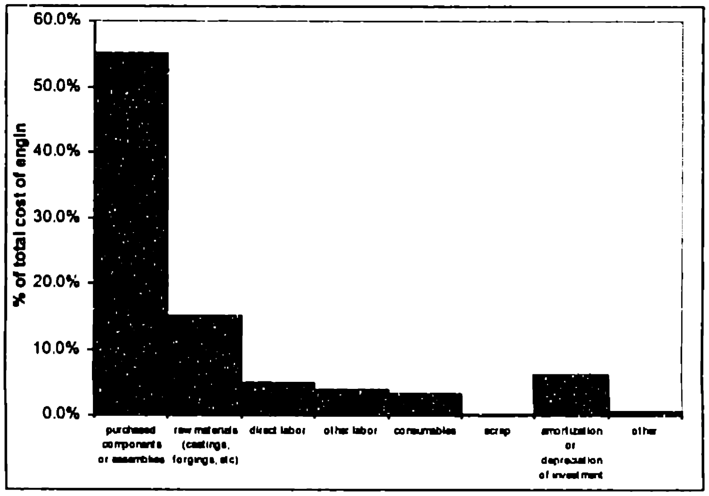


Figure 4-8 Median Numbers Shown from IMVP automotive engine company [IMVP, 1994]

Figure 4-9 demonstrates how a cell in Plant L can run with one worker or two workers depending on the takt time. If demand increases, operators are added from a cell that is not running at full capacity and if demand goes down operators are moved to other cells that need workers. If demand goes down operators could also do preventive maintenance or perform other value added activities.

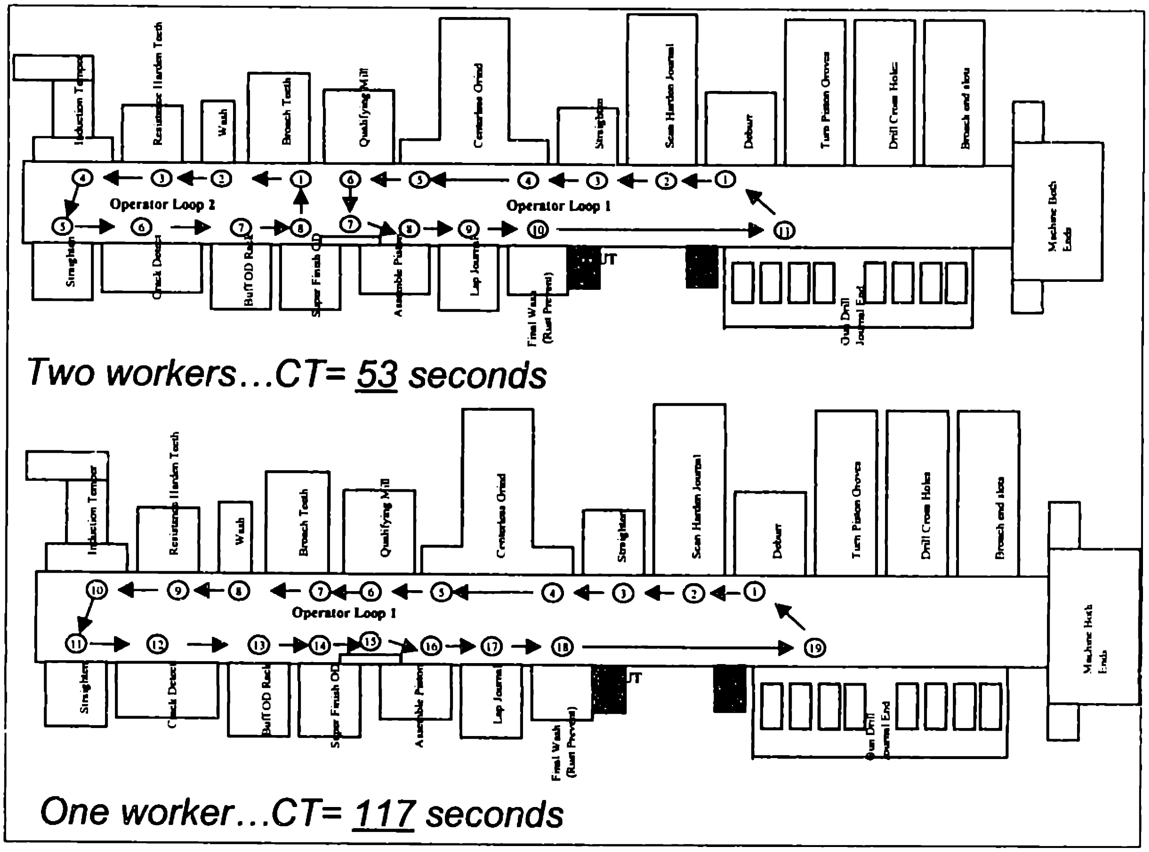


Figure 4-9: Sub-System design to achieve various demand volume rates

4.3.2 Aircraft Industry

The same concept of designing a production line to achieve minimum takt time is applicable in the aircraft industry. Whether designing a new system or trying to convert an existing manufacturing system, the designer should think about creating a system based on the minimum takt time to achieve a range of volume fluctuations.

For example, a company manufacturing turbine blades included in the takt time calculation the unpredictability of spare parts (figure 4-10). In this manner, the new cell could meet daily requirements of spare and new blades. For this company, having the ability to design and create a sub-system that is able to absorb that demand variability from markets like spare parts is the key competence goal in today's market.

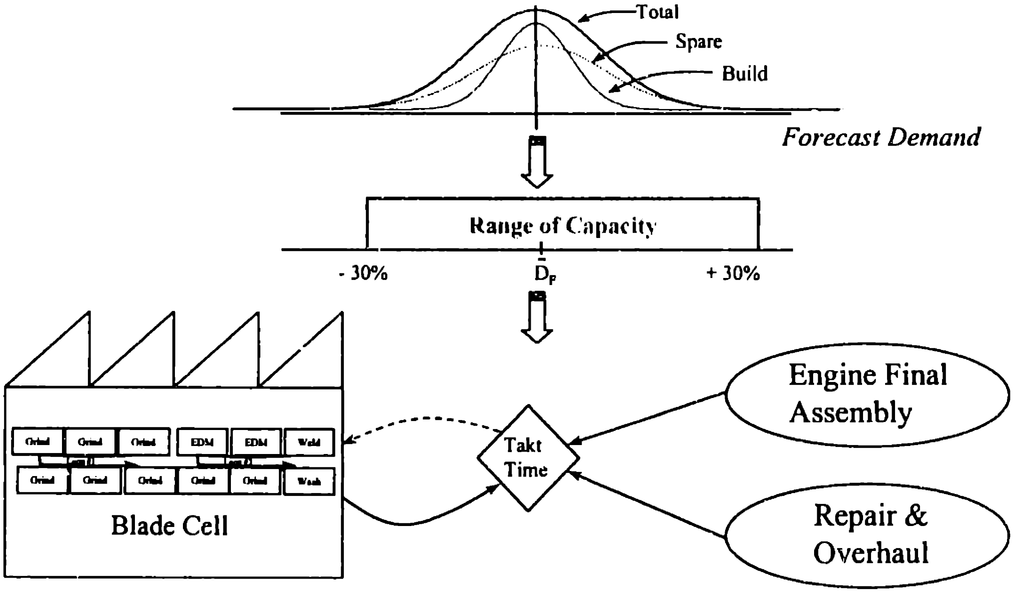


Figure 4-10: Blade Grinding Cell Designed to Meet Two Market Variability

The fundamental idea of designing a cell for minimum takt time is applicable to any type of product whether large and complex or small and simple; the difference is in the units of takt time. In the automotive and turbine blade the time is in seconds, for lower volumes like engines and planes the time unit is hours or weeks.

From the visits performed in the engine sector, it was observed that one company applied the idea of designing the line to meet a minimum takt time and was able to operate within a range demand volume (Figure 4.11). In this case, the takt time is in hours and since the assembly line is purely manual there is no limit to the upper takt time range (i.e. could be –40% or – 50%).

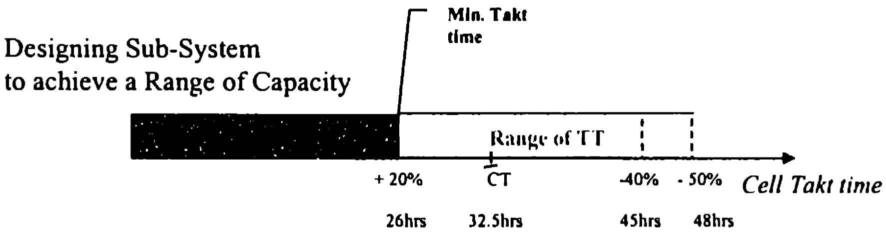


Figure 4-11: Achieving a Range of Takt Time in an Aircraft Company

4.4 Machine / Operation Design

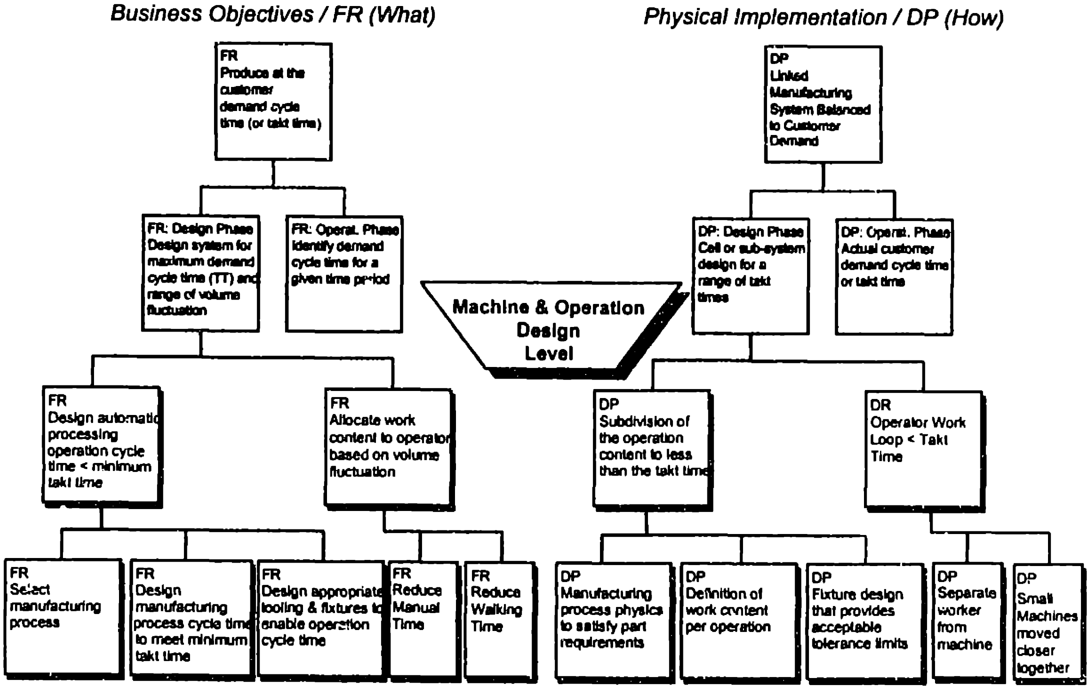


Figure 4-12: Decomposing the requirements and design parameters of the machine/operation level for a linked-balanced production system

The machine/operation level is always the most critical of all levels in the design of a Production System. It is the foundation of the Sub-system and System level (Figure 3-4). The design parameters at this level will affect the System's performance.

The cycle time of a production line or sub-system is dependent primarily on two time factors, which are the automatic processing cycle time of the machine or station and the work-loop cycle time[†]. Both times must be less than the minimum takt time in order for the sub-system to achieve and operate efficiently over a range of takt times.

Figure 3.13 shows an example of a work routine sheet. In this work routine sheet the work loop cycle time (manual + walking time), automatic processing cycle time, and takt time are identified. In this case, the work loop cycle time is less than the takt time. The use of the

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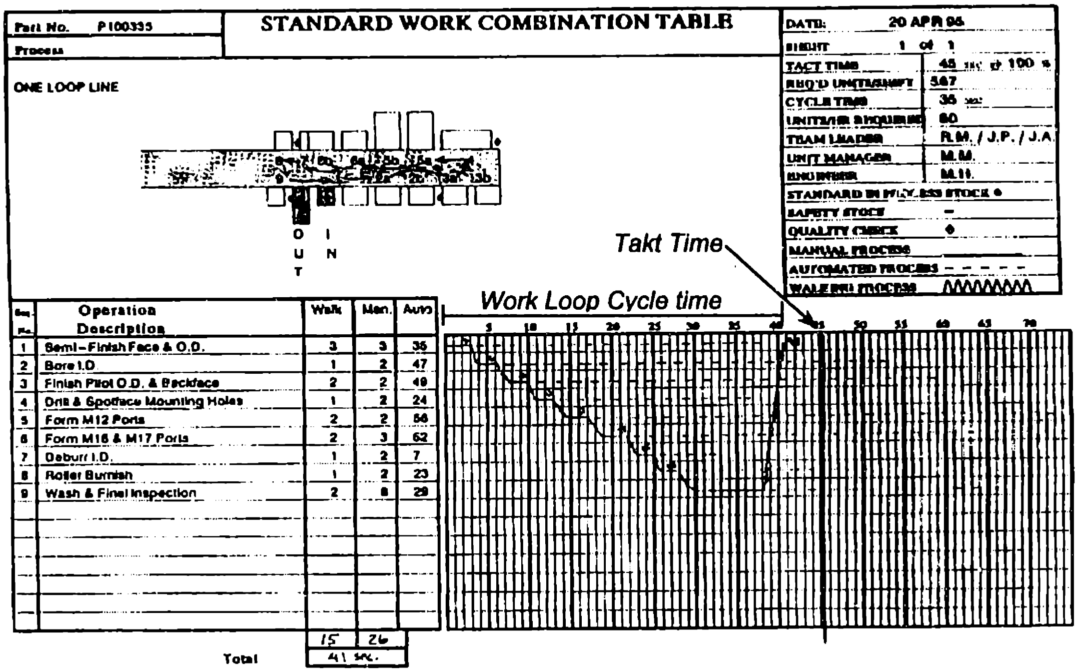
[†] Work loop cycle time is the time it takes the operator to complete his/her tasks. For example, in figure 3.9, the work loop cycle time is 53 seconds, which includes steps 1-8 (for loop #1) or 1-11 (for loop #2).

Standard Work Routine sheet helps identify the reasons for the work-loop not meeting the takt time. Appendix A gives a more detailed explanation on how to fill and use this worksheet.



Part No. P100335

Process

STANDARD WORK COMBINATION TABLE

DATE:	20 APR 96
SHEET	1 of 1
TACT TIME	45 sec @ 100 %
REQ'D UNITS/SHIFT	567
CYCLE TIME	35 sec
UNITS/HR REQUIRED	80
TEAM LEADER	R.M. / J.P. / J.A.
UNIT MANAGER	M.M.
ENGINEER	M.H.
STANDARD IN PROCESS STOCK ◆	
SAFETY STOCK	–
QUALITY CHECK	◆
MANUAL PROCESS	____
AUTOMATED PROCESS	– – – – –
WALKING PROCESS	ΛΛΛΛΛΛΛΛ

ONE LOOP LINE

Seq. No.	Operation Description	Walk	Man.	Auto
1	Semi-Finish Face & O.D.	3	3	35
2	Bore I.D.	1	2	47
3	Finish Pilot O.D. & Backface	2	2	49
4	Drill & Spotface Mounting Holes	1	2	24
5	Form M12 Ports	2	2	56
6	Form M16 & M17 Ports	2	3	62
7	Deburr I.D.	1	2	7
8	Roller Burnish	1	2	23
9	Wash & Final Inspection	2	8	29
	Total	15	26	
		41 sec.		

Figure 4.13: Example of Standard Work Routine Ssheet

The operator's time or (work loop cycle time) must be the controller of the cell's output instead of having the automatic processing time of a machine control the output of the cell. The output of a cell controlled by the operator's cycle time enhances the flexibility of the sub-system or cell because operators can be added or removed to match the demand takt time. Both components of the work loop (manual and walking time) need to be less than the takt time in order to reach a balanced production to the customer's cycle time. Separating the worker from the machine and from the part is needed to achieve volume flexibility and reduce the time of the operator at the station so that he/she can continue to the subsequent operation. For example, in machining, the operator manually loads the part into the fixture (complex rotational movement), hits a walk-away switch and moves to the next machine while the machine performs its operations autonomously (Figure 2-12). When the part is done, the machine will automatically unload the part and present it to the worker for easy retrieval. On the other hand, if the machine is designed so that the worker needs to stay at the machine (i.e. no man-machine separation), then the manual time increases which causes the number of operators to increase in the cell (# of operators = manual time/takt time).

Since all work loops within a cell are not running at exactly the same cycle time, it is necessary to apply mutual relief movement to make up for delays in some processes [Monden, 1993]. This means that if the person in the subsequent process is delayed, the preceding worker should setup and take off the work on the subsequent machine. When the subsequent worker returns to his initial position, the preceding worker should hand the work to him immediately and go back to the preceding process. The same strategy would apply if the preceding worker was delayed. The mutual relief movement not only helps reduce variability that exists from loop to loop but also helps increase the ability of operators to work as a team.

The second controlling variable of time in a cell or sub-system is the automatic processing time, like machining, testing and others. This automatic processing time must be less than the minimum takt time. This means that the goal is no longer 100% machine utilization, but 100% worker utilization and that machines are designed for cell integration.

At Plant L, the machines and equipment are designed to meet the minimum takt time by subdividing the automatic operations and perform the operations in series instead of parallel. On the other hand, Plant M usually buys machines and equipment that exists on the market but are not designed to meet the requirement of producing at the minimum takt time. Plant M buys machinery that can produce in large quantities in order to minimize the unit cost of the product (economies of scale). For example, Plant M uses a continuous furnace (Figure 4.15) to anneal or stress relieve the rack bar after some machining processes were done on the rack bar. This machine meets the requirement of making large quantities therefore minimizes unit costs; however, the throughput time is almost 2 hours therefore it is not very responsive to changes in demand and cannot produce at the minimum takt time. Conversely, since the relief of residual stresses is a time-temperature-related phenomenon, parametrically correlated with the Larson-Miller equation, it is feasible to design a machine that meets minimum takt time for stress relieving (Figure 4-14). In other words, similar relief of residual stresses can be achieved by holding a component for shorter periods at higher temperatures.

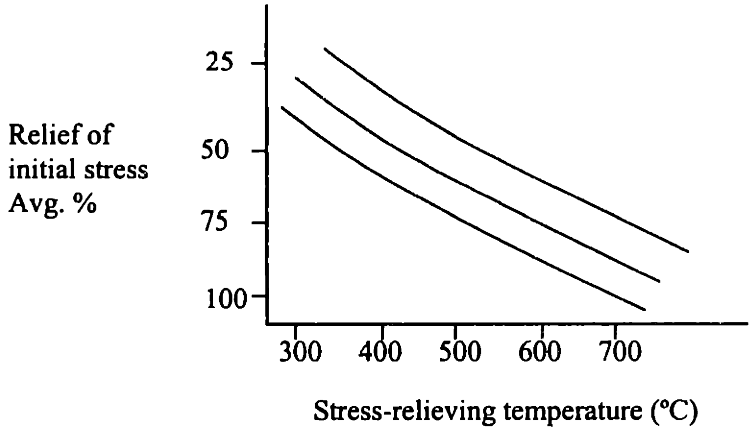


Figure 4-14: Time-Temperature Phenomenon of Relief of Residual Stresses

For this reason, Plant L decided to modify an induction-tempering machine to achieve rack bar specifications and meet the requirement of minimum takt time. Other requirements when designing the machine were a form factor (5' in width), man-machine separation, higher flexibility (quick changeover), lower tooling/maintenance cost and higher quality output (machine reliability). The machine can produce a part every 40 seconds. The bar can be easily located and referenced in the fixture of the machine, so that the operator can load the part in less than 3 seconds.

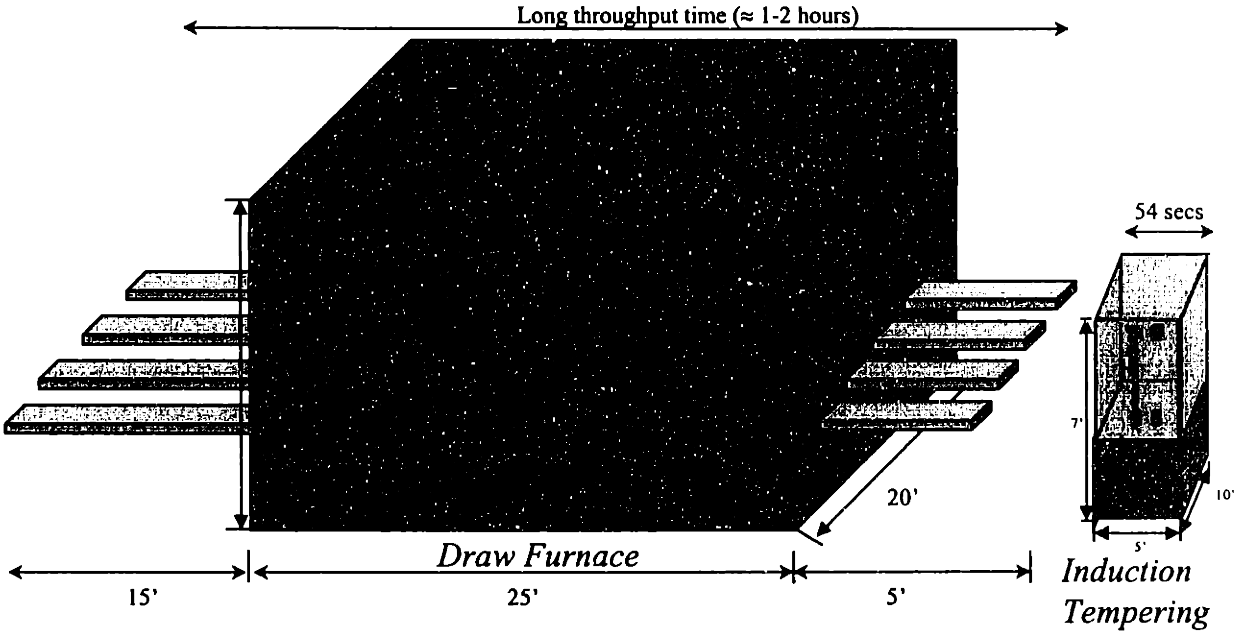
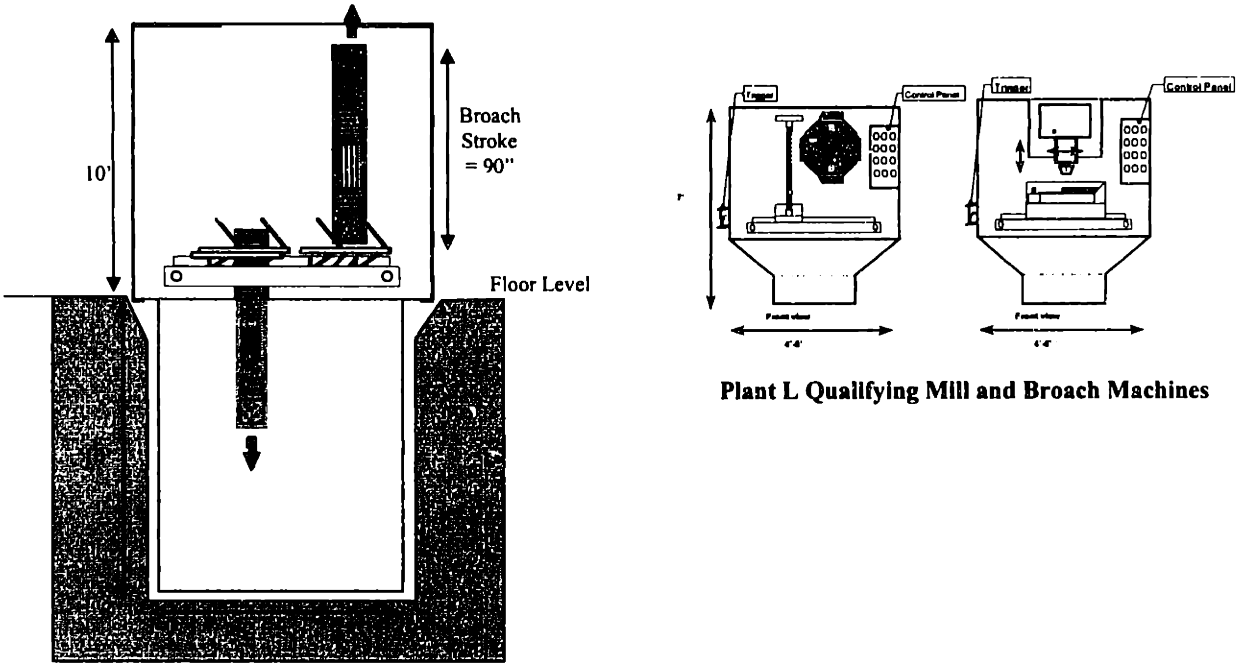


Figure 4-15: Draw furnace versus induction tempering

Another example in the fabrication stage of the rack bar is the broaching operation to cut the rack bar's teeth. Plant M uses a vertical broach machine that can make a part every 6 seconds (Figure 4-16). Plant M's broach machine meets the design parameter of having the machine cycle time to be less than the minimum takt time yet its design does not achieve other design attributes that support the system design requirements such as, form factor, man-machine separation, quick changeover, low tooling cost and others. Since the cycle time is very fast, there has to be an operator "tied" to this machine making him/her inflexible to operate other machines/equipment or even inspect the parts. The rough and finish cut of the teeth is made in one single 90" vertical stroke. Consequently, it is necessary to set the machine into a trench on the floor (~10' deep). This design makes the machine completely inflexible in terms of re-location and serviceability. This design is again presenting the mentality of justifying the design and equipment in terms of unit cost and not in terms of "time-cost".

On the other hand, Plant L subdivided the operations of cutting the teeth into two machines (Figure 4-16). First, there is a qualifying mill that removes some material from the surface of the rack bar then the rack bar is placed into the horizontal broach machine to cut the shape of the bar's teeth. Both machines are designed to meet the minimum takt time to achieve volume flexibility by separating the worker from machine and reduce machine width to a form factor of 4'-5' that eliminates walking time.



Plant M Broach

Plant L Qualifying Mill and Broach Machines

Figure 4-16: Broaching operations at Plant M versus Plant L

In the same manner, the testing equipment at Plant L was subdivided into 5 different stations in order to meet the minimum takt time that the cell was designed to achieve. At Plant M, the testing was done in one machine running at 80 seconds. Since a cycle time of 80 seconds was much slower than the rest of the line which runs at 10 seconds, Plant M, incorporated 8 functional tests machines in the line to run them in parallel.

From figure 4-17, it can be seen that in the lean plant, the burnishing operations were also subdivided into two different stations running in series instead of processing the completed burnishing operation in two parallel stations.

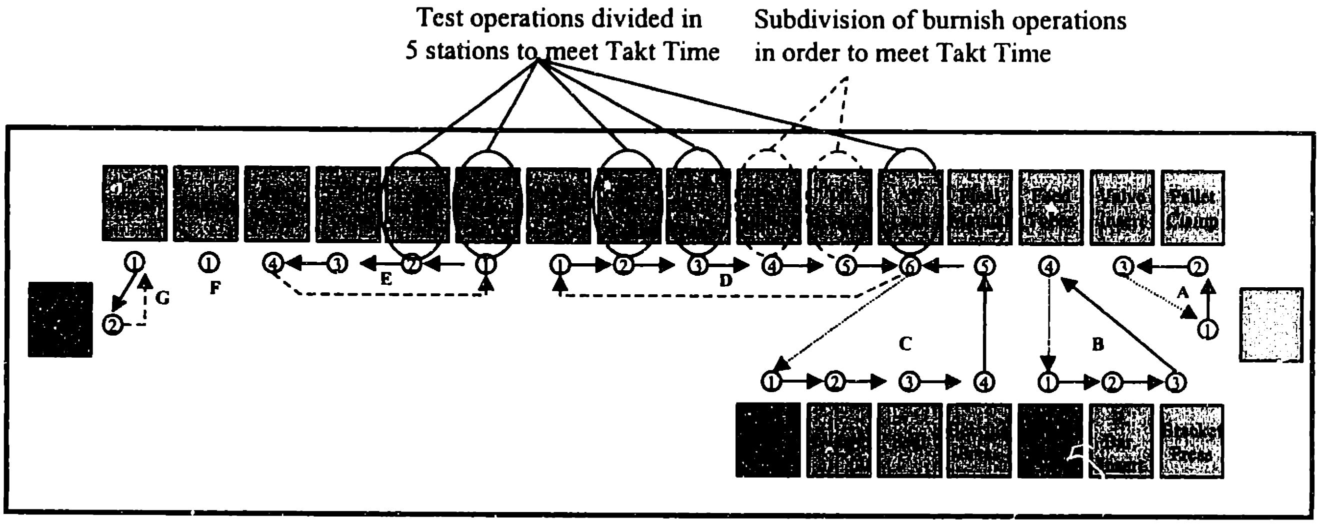
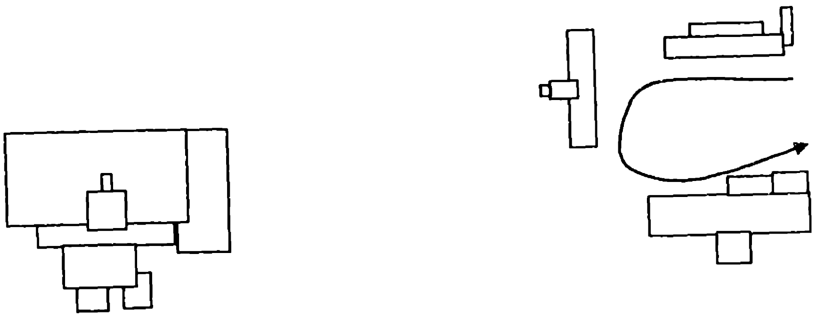


Figure 4-17: Subdividing operation in assembly cell at Plant L

4.4.1 Aircraft Industry

Subdivision of machine operations in the aircraft industry is sometimes more difficult than in the automotive industry because of the part size and component material. However, there are many opportunities for improving in those areas as well as in the areas of machining small parts.

About ten years ago, the industry logic was that the best manner for grinding turbine blades was by aggregating all the operations into one "high speed", 12 axes of motion machine. That 'one' machine could not meet then minimum takt time when the machine was analyzed as a system. Nowadays, the industry is rethinking the problem and defining the solution in a much different manner. One company subdivided the operations from the 'monumental' 12 axis machines designed in the late 80's into three machines grouped in a U shaped cell configuration called an "Interim Cell" [Black, 1991]. Throughput time and inventory subsequently decreased by more than 40%$^+$. However, the problem is that these machines were not really designed to operate in a system. The design of machines did not facilitate volume flexibility, minimum takt time, man-machine separation, ergonomic loading, single piece flow or the idea of building to customer takt time.



Automated Blohm Grinder

'Interim' Cell

Figure 4-18: Subdividing Operations to meet System's Takt time

The next generation of cell occurred in another engine company than the company previously mentioned. The machine cycle times were subdivided to be less than or equal to the lower range or minimum takt time. Instead of having only one super fast machine to grind the blades, there are eight smaller, less complex, 3-axis machines in a grinding cell. Figure 4-19 shows an example of a typical blade-grinding machine from that cell. The machine was designed with the requirement of achieving a minimum takt time, a form factor of 4'-5' in width and the man-machine-fixture interface to accomplish the goal of separating the worker from the machine to meet a range of volumes by adding or removing operators.

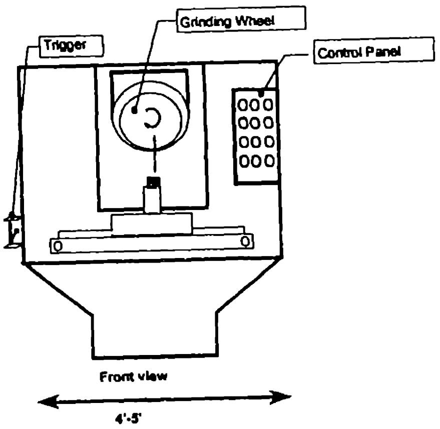


Figure 4-19: Blade Grinder Machine designed to achieve minimum takt time

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[+] Personal interview with manufacturing engineer at Company A

In the aircraft engine assembly, the same principle of subdividing the operations can be applied. When the operations are manual, the number of operations or stations depends on the takt time; therefore, the number of stations should be:

$$\frac{\textit{Number of Stations}}{} = \frac{\textit{Total Assembly Time}}{\textit{Minimum Takt Time}} \tag{4.1}$$

In this way, the stations will be subdivided to meet the customer demand cycle time. One company from the aircraft engine sector did something similar to this. The final assembly line is divided into several stations to create a single piece-continuous flow and to meet the takt time. The number of stations/operations was determined by using the relationship defined by equation 4.1. For example, if assembling a compressor rotor takes 60 hours and the takt time is 20 hours, the assembly of the compressor rotor should be subdivided into 4 main operations or stations (figure 4-20). The compressor assembly is moved from station to station after assembly is completed at a station.

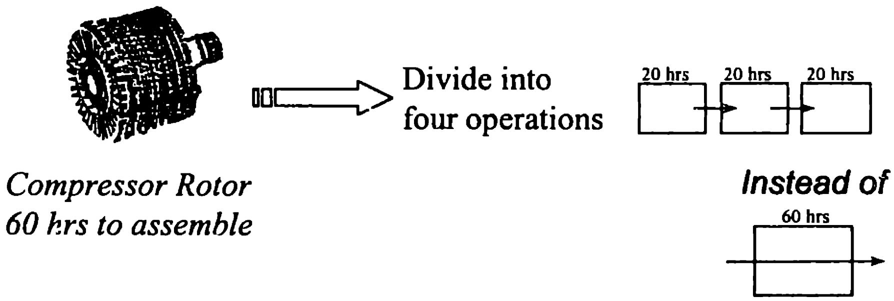

Figure 4-20: Sudivision of operations to achieve minimum takt time in compressor assembly

4.5 Machine Design Similarities in both, automotive and aircraft industries

The functional requirements and design parameters of balanced production are very applicable whether it is aircraft, automotive or any other product. At the system level as well as the machine/operation level, the functional requirements and design parameters are appropriate for both industries. The primary difference is the pace of production or takt time. In the automotive industry, takt time is expressed most of the time in seconds because of the high volumes, while in the aircraft industry takt time is in hours because volume is medium to high.

The next figure (Figure 4-21) demonstrates the machine design similarities whether it is grinding a turbine blade, broaching a rack bar for an automotive steering gear or tempering a rack bar.

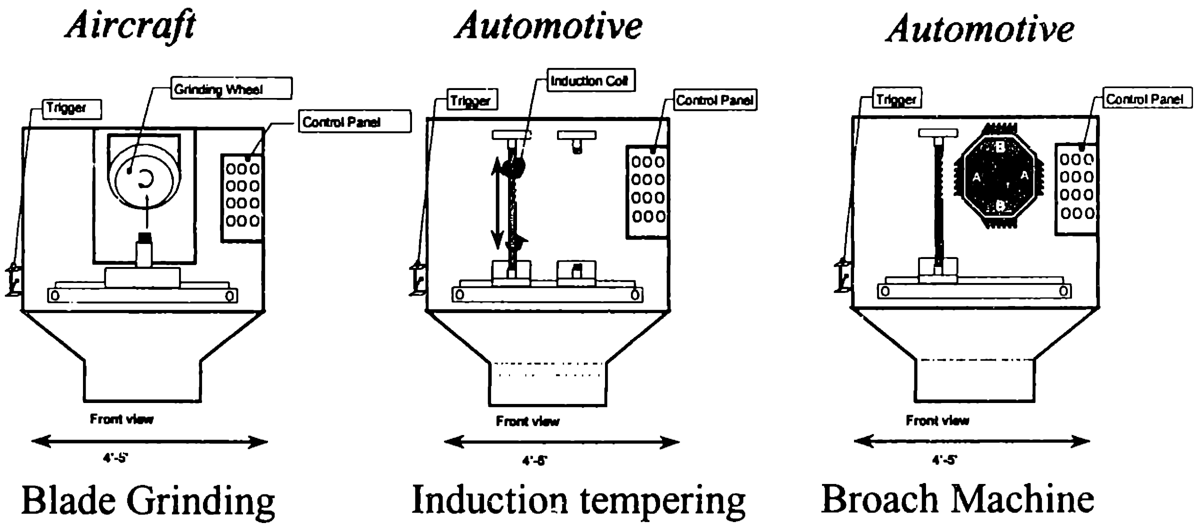

Figure 4-20: Machine design similarities across industries

The three machines above were designed to meet a minimum takt time, produce one piece at a time, have a form factor of 4'-5' in width, use simpler linear motion drivers, and man-machine-fixture interface to allow the worker to load and unload parts ergonomically in one motion.

5

Leveled Production System

Unless companies distribute work evenly by leveling (smoothing) production, both the minimum inventory condition and response to sales velocity of each product sold in the marketplace is impossible to achieve. Level production is the ability to make the quantity and mix of products demanded by the final customer within a given time interval (demand interval). Making an even mix in a production line distributes the workload amongst all processes and thereby uses resources effectively with minimum inventory. In the supermarket analogy, if all customers decide to buy the same product at the same time, shortages are certain to occur. However, in a level production, customer demand is spread out over time and with different mixes of products, the supermarket is able to replenish the shelves with product a little at a time, and thus avoid shortages. Suppliers also benefit from leveling because suppliers can make deliveries every few hours; thereby reducing the inventory in their plants. Suppliers will face difficulty if they can not produce with a response time less than the demand interval[+].

Level production occurs over two planning horizons. The first is the monthly adaptation, which is achieved by a monthly planning of a master schedule showing the average daily production level of each process in the plant. The second stage is the daily adaptation of production. This stage is achieved with the use of a Heijunka box to level and schedule the production of the final assembly line for the day and then use a pull system or Kanban system to control the lines that feed the final assembly. This second stage is leveling based on the

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[+] The next chapter will define in more detail the concepts of response time and demand interval.

man-hours it takes to produce different products going through the line. The first stage of leveling is based on quantity and not time.

To illustrate this first planning horizon, assume that there is demand of 5,000 units of A, 2,500 units of B, and 2,500 units of C per month. Using EOQ estimates, companies will often produce the entire demand requirement in one lot (Figure 5-1a). This is done to accommodate the setup time, which has been assumed to be a constant. In other words, reducing setups has not been considered and large lot sizes have been used to keep the number of changeovers at a frequency justified by the EOQ calculation. The ideal production sequence will be to produce in smaller batches proportionally distributed across the entire month (Figure 5-1b). Shipping smaller quantities more frequently to the customer will in turn minimize their inventories. Even if the demand interval of the customer is once per month, this monthly amount should be leveled and mixed in with other product demands. This helps preceding cells to produce at a consistent rate and allows uniform allocation of resources (i.e. workers) to meet customer demand.

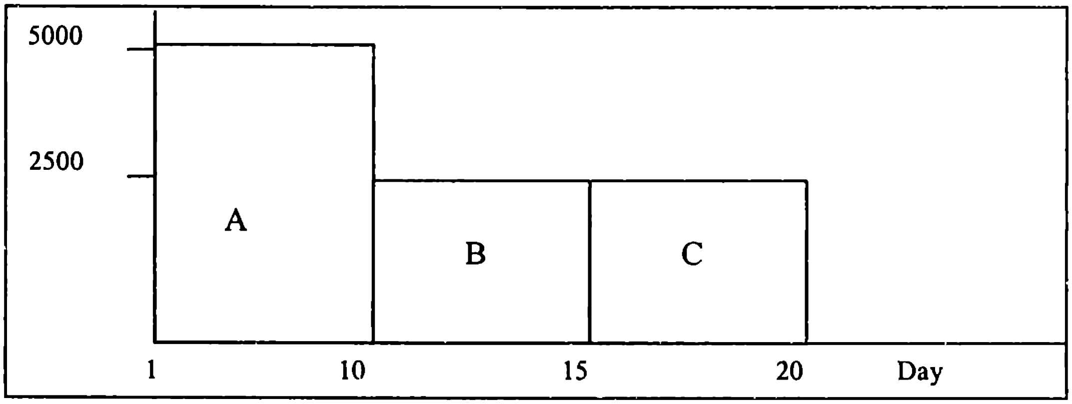


Figure 5-1a: Production Plan Before Leveling

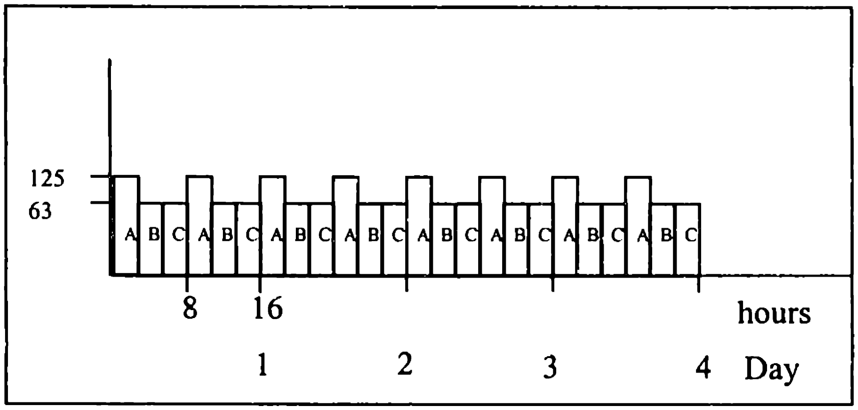


Figure 5-1b: Leveling Quantity for Customer that Pick-Up Once per Shift

Leveling of man-hours can also be performed on the labor requirements for different products on the same line. For example, assume A, B, and C are produced on the same line at 40, 30 and 20 minute cycle time respectively and that the takt time for the line is 33 minutes. If the product is produced in some sequence (A, B, C, A, B, C) the line would not stop because the average cycle time is 30 minutes, which is very close to the takt time (Figure 2a). However, if product A is produced in lots (Figure 2b), the 33 minute takt time will not be able to complete A because A requires 40 minute cycle time. This requires more workers to complete the work within 40 minutes.

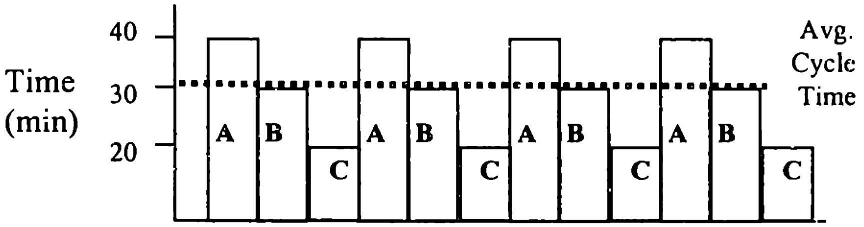


Figure 5-2a : Sequence that enables Assembly within average cycle time

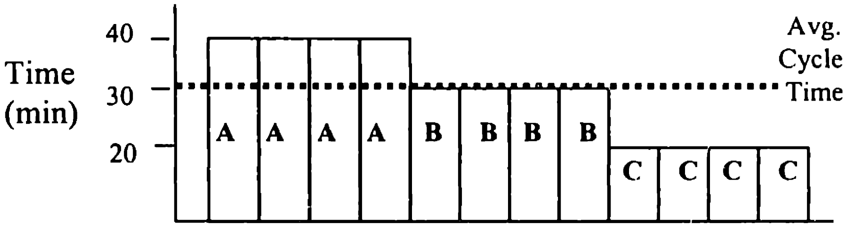


Figure 5-2b : Sequence that causes line stoppage

5.1 Manufacturing System Design

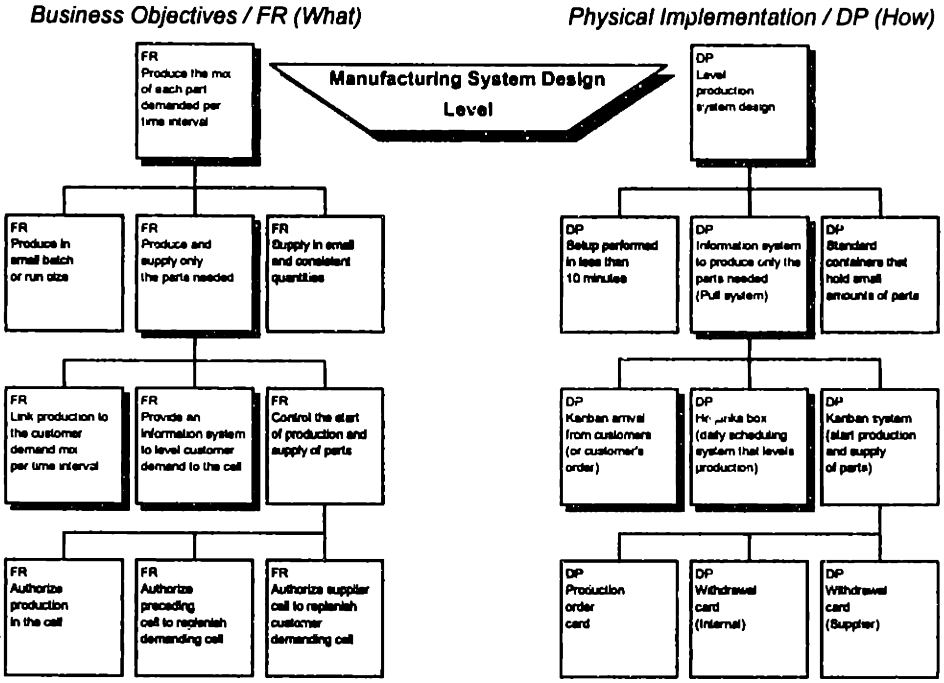


Figure 5-3: Decomposing the requirements and design parameters of the manufacturing system level for a Leveled Production System

Being 'lean' does not mean to eliminate forecast demand and use only a Kanban system to plan and control the production on the floor. Forecast demand should be used to plan capacity. Companies like Toyota and Nissan use a yearly production planning, which then it is revised in more detailed with a three month span, then a 10 day and finally a daily adaptation [Monden, 1993].

Monthly adjustment of a plant production system is possible if a given plant is not operating at maximum capacity. The greatest challenge is to effectively make daily adjustments to production to meet current customer takt time. Current Material Requirement Planning (MRP and MRPII) computer systems can not efficiently control daily production because an MRP system does not see the actual production inside the plant until it is regenerated, which usually happens once a week. For this reason, it is difficult to adjust to daily changes in mix and volume on a timely basis with current MRP systems. Information system for production control must originate from the subsequent station, cell, plant or customer (kanban system).

In this way, the system pulls what is really needed instead of pushing an inaccurate estimate of demand.

In addition to the information system (Kanban System), a Heijunka box is used as a production planning method in which the (typically mixed) sequence of items to be produced during a given day are determined, taking into account process loads and capacities, as well as external demand. That information is used to establish the production sequence at the start of the first operation; the sequence is then maintained throughout the remainder of the flow-oriented production process [The Toyota Production System, 1992]. This is different from traditional batch production, which not only generates extra inventory, but also tends to concentrate work on certain parts of the production process (and thus, on only a certain segment of production personnel) at a given time.

A Heijunka box takes the available time and sub-divides it into amount equal to the takt time (Figure5-3). A slot or bucket with a kanban card will be placed signifying what is to be produced or picked up for the specific takt time.

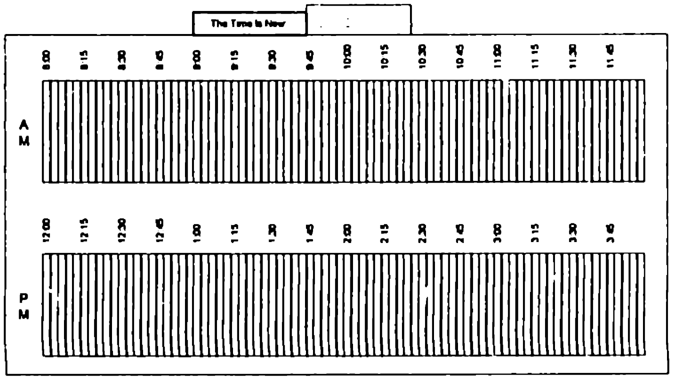


Figure 5-3: Example of a Heijunka Box

5.1.1 Automotive Industry

Currently most companies in the automotive industry use MRP or MRPII to plan and control their production. Plant M creates a master schedule every six months that is updated every week. This weekly plan is then used to schedule the production of all the machines in the fabrication area as well as all the assembly lines independently. That is, the fabrication department does not know the actual production needs of its customer, which is the assembly department. Since this weekly planning can not be updated during the week and does not look at what is occurring on the floor, the plan includes additional production due to operator's absentee or extra breaks, line and station adjustments and scrap rates in order to achieve the production goal. The problem is that most of the time all this "just-in-case" production ends up as inventory.

Since Plant M is "pushing" their production, sometimes they could be making the incorrect pat number. Several times the assembly line at Plant M had to shut down because the correct or needed part coming from fabrication was not produced.

At Plant L, although its current state is not the ideal design, it is at a better stage than Plant M. Plant L uses MRPII to plan monthly with weekly releases to control the production of the final assembly only. Then the final assembly controls the production of the other preceding fabrication cells with a pull system. Team leaders of fabrication cells receive weekly and daily scheduled production, but an empty cart coming from assembly is what initiates the production (Figure 5-4). Implementing a pull system at Plant L helped achieve the goal of producing and supplying only the parts needed. The implementation of the pull system eliminated the problem of having any shortages. The pull system was implemented not only internally but also with the majority of the suppliers.

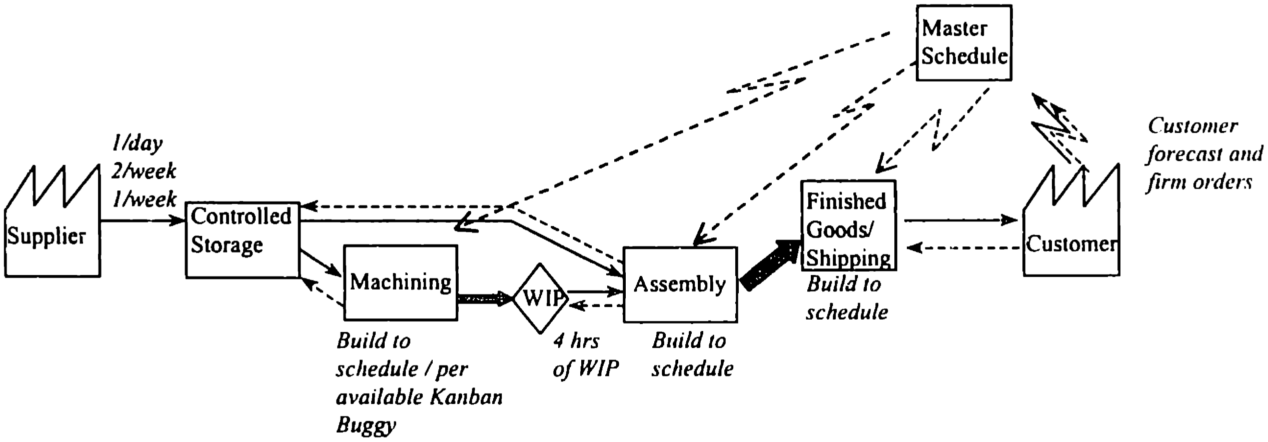


Figure 5-4: Current status of Plant L

Plant L plans to implement a true pull system controlled by a Heijunka box to create a more leveled production. The customer will make a pick up every two hours and leave kanban cards of the parts used the two previous hours. Then every two hours the Heijunka box will be re-scheduled depending on what was used by the customer. This means that kanban cards posted on the Heijunka box will determine the production in the final assembly. The assembly will pull from the fabrication lines every hour and the fabrication lines will produce only what is pulled by assembly. This system can be seen in Figure 5-5

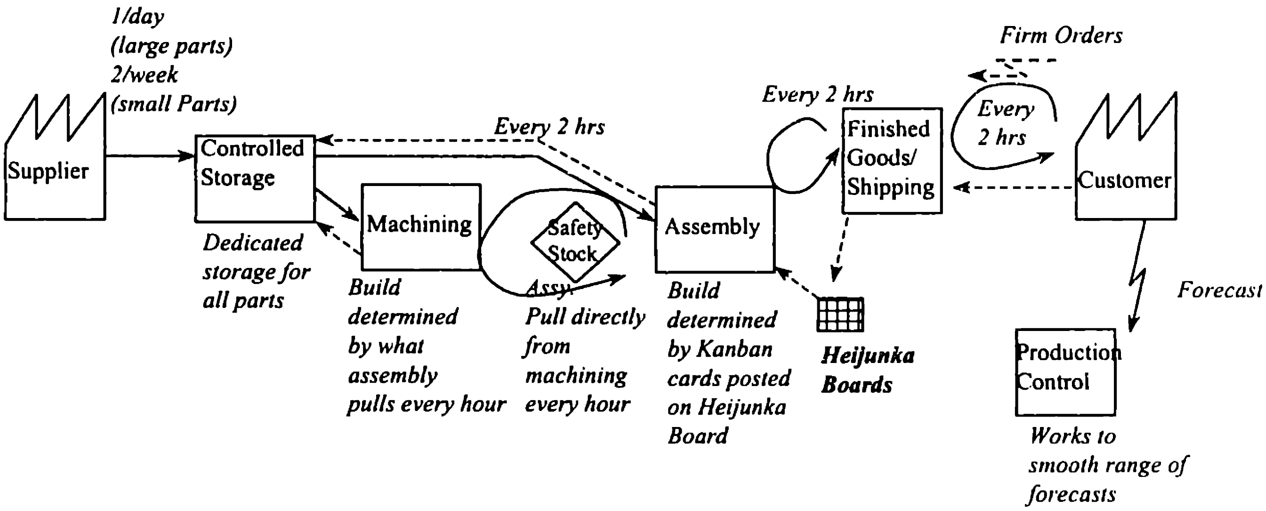


Figure 5-5: Future status of Plant L

5.1.2 Aircraft Industry

The concepts of leveled and balanced production are two of the most important concepts in order to achieve greater gains in productivity and inventory turns. Leveled production in the aircraft engine sector will mean to produce the quantity and mix of engines demanded in the time interval specified by the customer. The production requirement of engine type needs to be distributed evenly over the time interval to achieve this goal.

Most of the companies visited in the small aircraft engine sector were making few engines at the beginning of the month and much of the production aggregated into the end of the month.

It can be seen from Figure 5-6, that the average engine production for one month at Company A is 17 engines. The company argued that the primary reason for having higher production output at the end of the month versus the beginning of the month (Figure 5-6) was due to part shortages and not having the necessary modules at the moment of assembling the engine. Another possible cause for the "hockey stick effect" at Company A is having monthly production requirements instead of daily or weekly. Not sequencing correctly the engines could also cause Company A suffer the effect of uneven production. Company A assembles two types of engines on the same line. If the production of these two types of engines is not sequenced correctly, resources could not be allocated properly, thereby causing some engines to be late. One possible solution will be to classify the various engine types on a production line by man hours required into three groups (small, medium, and large) then level try to level the production according to the man-hours required.

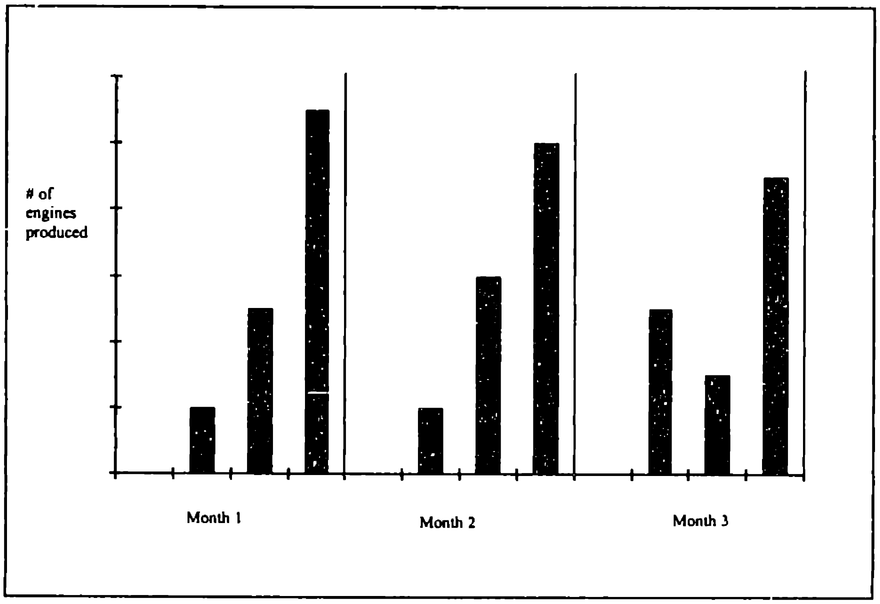


Figure 5-6: Typical production output at Company A ('hockey-stick-effect')

Conversely, Company C leveled and smoothed a monthly production of engines to weekly requirements (Figure 5-7). One difference in this company versus company A is that the production line was designed to be product/customer oriented. In this manner company C can easily level the customer demand and in some manner sequence the engine production in order to fully utilize the workers.

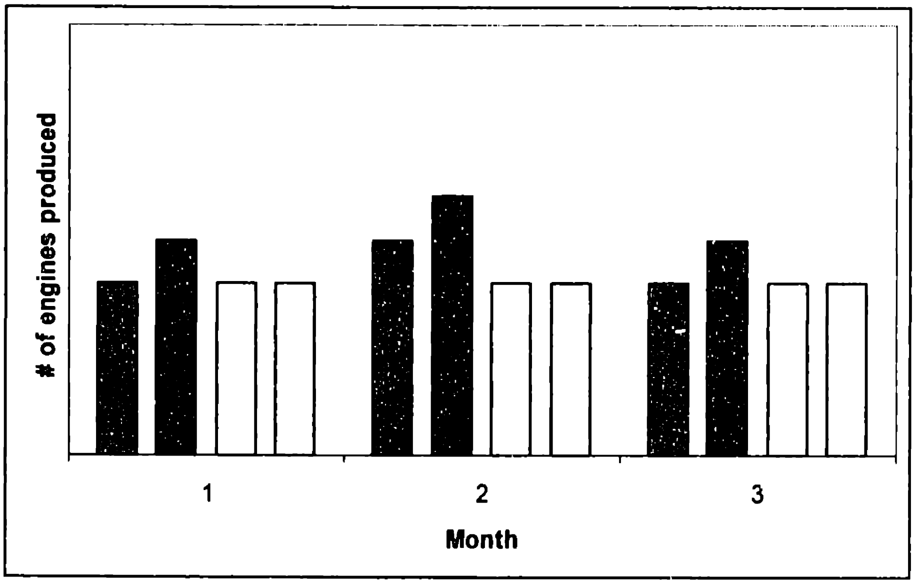


Figure 5-7: Smoothed production output at Company C

However, even if Company C leveled their demand and sequence of the engine types but does not have the necessary components, the company will never be able to achieve the customer's demand. For this reason, Company C implemented a pull system internally with some suppliers to ensure the availability of parts. In this manner, Company C achieved a 97% availability rate of large parts coming from suppliers and 100% availability of small common parts like nuts, bolts, clamps, etc.

5.2 Manufacturing Sub-System Design

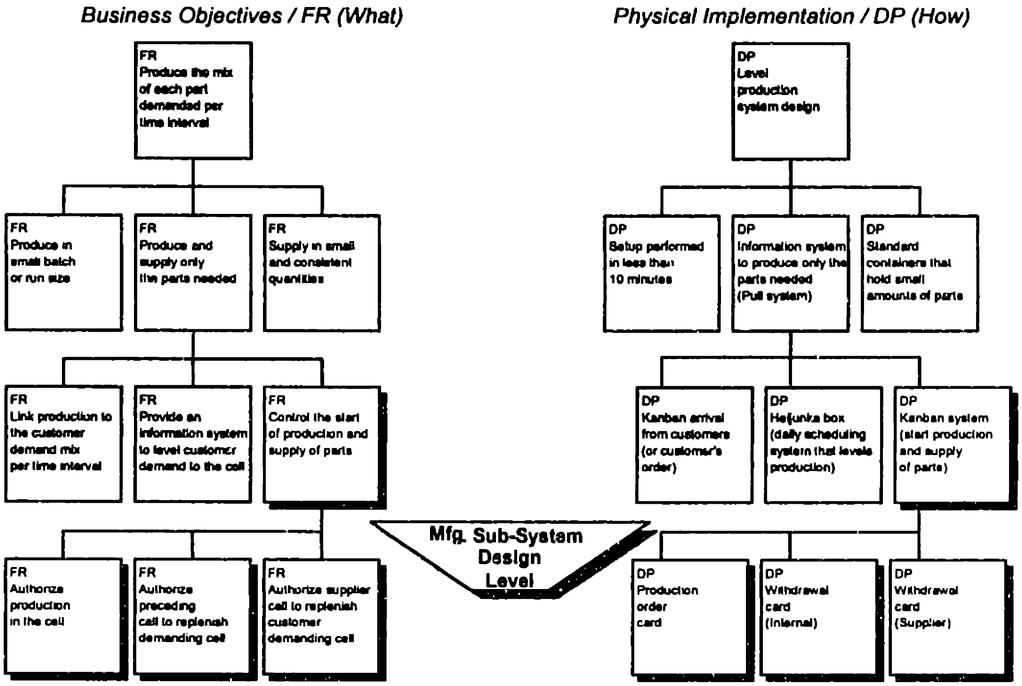


Figure 5-8: Decomposing the requirements and design parameters of the manufacturing sub-system level for a Leveled Production System

As stated in the previous section, an MRP or MRPII system should not be used to control the production of the floor. The system that controls the start of production needs to be close to the manufacturing process. The signal to control production needs to be in constant interaction with the different sub-systems to make sure that it is triggered at the right moment for the needed parts.

In the Toyota Production System, a kanban card is usually used as the signal of production. A kanban is a signal to either produce or withdraw. Kanban can be a card, dolly, mark on the floor, or any other low cost device. Toyota uses the Kanban system to link the entire supply chain. For a large assembly shop at Toyota there are 20,000 kanbans processed per shift [Toyota Production System, 1992]. The most important aspect of a kanban system is that it controls the daily adaptation to demand.

5.2.1 Automotive Industry

As it is with any other mass producer, Plant M, *controls* the production of every production line and machine with a planning system (MRP) and 'pushes' the production to the next process or machine. The problem with this system is that assembly could be demanding Part A from the preceding process yet the preceding process is making Part C.

Plant L obtains at least a 3-6 month forecast from its customers in order to estimate needed monthly capacity update suppliers on what needs to be delivered. However, in all likelihood, these estimates will change from day-to-day. Additionally, the actual production volume is sometimes increased or decreased from the volume depicted in the forecast table that the customers send. These adjustments to the production forecast are made via the Kanban system as a fine-tuning measure.

The Kanban system in Plant L controls the entire production within the factory (Figure 5-9). There are three main types of kanban used in Plant L: production ordering kanban, internal withdrawal kanban and external/supplier withdrawal kanban. The production starts in the final assembly cell when the production control person places a production ordering kanban card in the final assembly stating the quantity and type of product needed. To control the production between the final assembly and the fabrication cells, an empty cart is used as the medium to triggered the production in the fabrication area. Most of the time there are four carts in total, one in the assembly area, the other being refilled and two full carts waiting to be picked up from assembly. These carts contain an average of 4 hours of production.

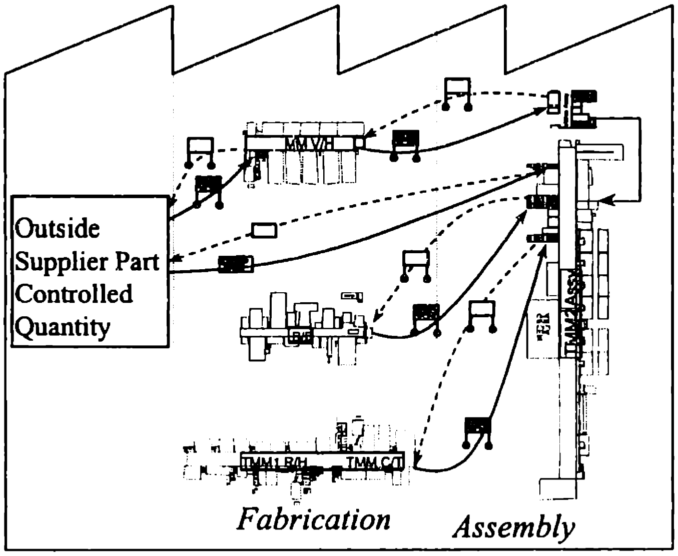


Figure 5-9: Kanban implementation at plant L

One card in final assembly represents 20 parts. Once 20 parts are completed, the card is scanned and information is sent immediately to let suppliers and production control know the number of parts done and waiting for shipment.

5.2.2 Aircraft Industry

It was demonstrated that part shortage is the biggest problem in two out of three companies from the Lean Aerospace Initiative engine sector case study. Company B tried to minimize the part shortage problem by implementing a kanban system between final assembly, material storage rooms and sub-assembly areas. The result was that most of the time <u>all</u> the kanban carts were either empty or full. The kanban system never worked because discipline was not maintained and production in final assembly was not leveled, causing engine production to vary from one week to another. Having very unpredictable and variable consumption rate of kanban containers (i.e. unleveled production of engines) caused the containers to be either all full or all empty.

Company C is currently using a kanban system to control the start of production and supply of parts internally and externally. The kanban system observed at Company C was very similar to the one implemented by Plant L.

5.3 Machine/Operation Design

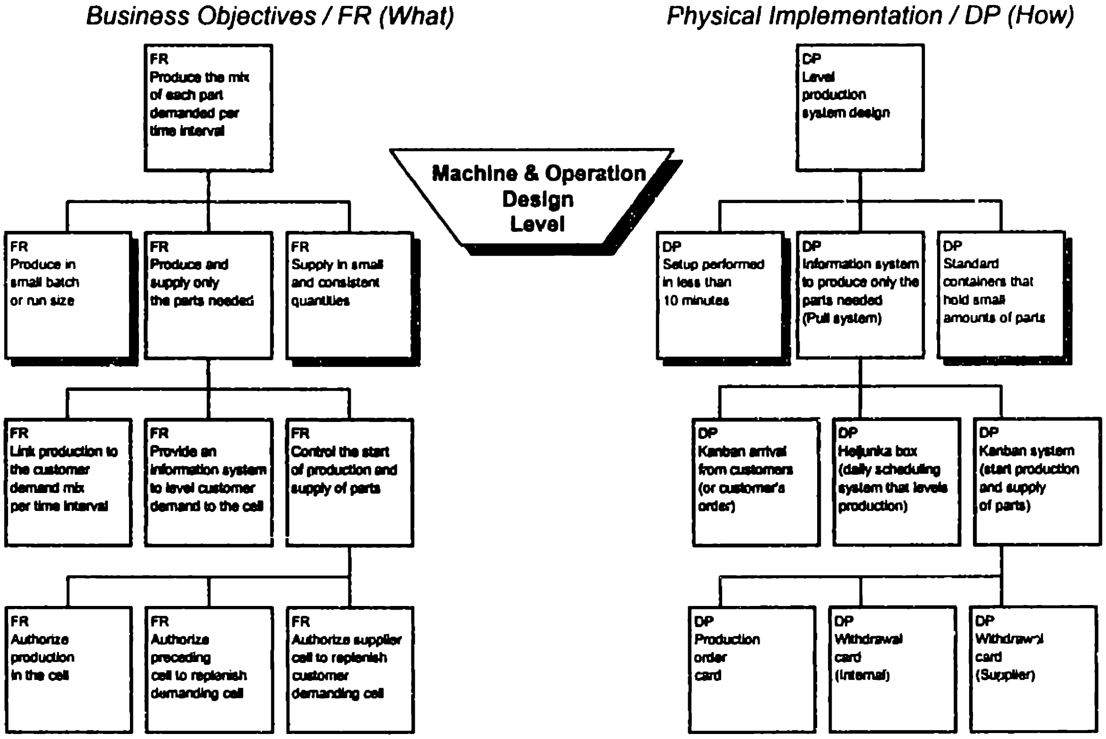


Figure 5-10: : Decomposing the requirements and design parameters of the machine/operation level for a Leveled Production System

To achieve a leveled production and adapt quickly to changes in demand, it is necessary to perform fast changeovers. Shigeo Shingo was the pioneer in developing techniques to achieve what he called "single minute exchange of dies" (SMED). SMED suggests that there are two types of setup operations [Shingo, 1986]:

Internal setup – setups operations that can be performed only when the machine is stopped, such as mounting or removing dies.

External setup – setup operations that can be completed while the machine is running, such as transporting dies to or from storage.

When designing new machines or equipment, the designer should design for quick changeover time, instead of waiting until the equipment is on production and then start to use the SMED techniques.

5.3.1 Automotive Industry

Most of the equipment in Plant M has a changeover time in the range of 1-2 hours. This long changeover time does not create the needed flexibility to adapt quickly to changes in demand and to achieve level production. In the assembly lines, when changing from one model to other, the line needs to be stopped to remove all the pallets, change fixtures and programs in the testing machines. Each assembly line can produce an average of 3 models.

In Plant L, the final assembly line can assemble five different models ranging from long stroke to medium stroke, left and right hand steering gears. The product is tested in five different stations each of them performing a different test. In a testing machine, a 'driver' that turns the steering right and left grabs the upper part of the pinion to perform the test. When changing from left-hand gear to right hand gear, the 'driver' needs to be moved and rotated 45° because the pinion for right hand gears is oriented at a different angle. Plant L designed a fixture for the spindle (Figure 5-11) so that when changing from one model to the other the operator will only need to remove a pin, move the spindle to its new location and replace the pin for security purposes. The changeover from one model to another in the test machines takes less than one minute. The design is simple, standard and very inexpensive. In Plant M the solution of quick change over for new testing machines was very different and more expensive. Plant M placed two spindles, one for each model (left hand and right hand) in the same machine. The idea of placing two spindles was to achieve the zero changeover time by automatically changing over from one model to the other. However, Plant M had to pay a higher price and created a more complex machine that is only one minute lower than Plant L in the changeover time of that specific machine.

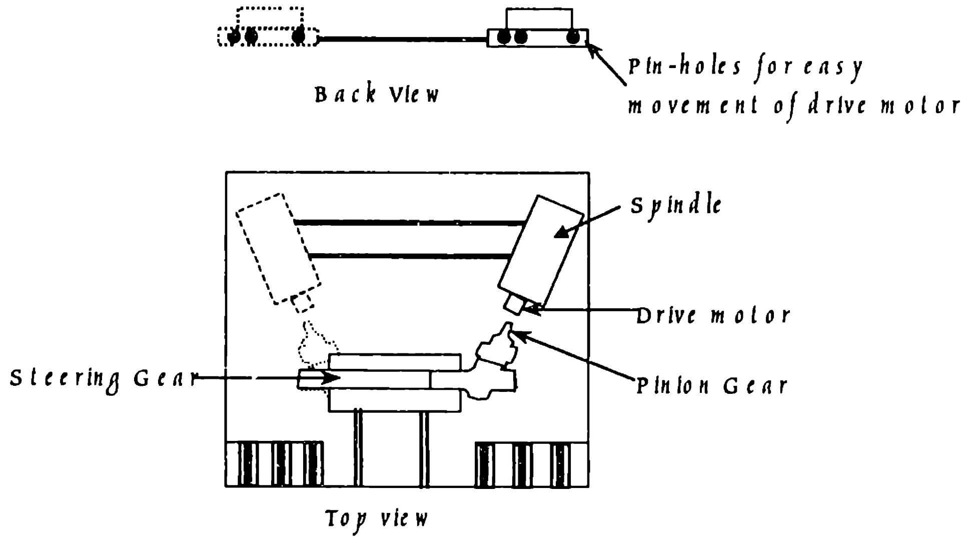


Figure 5-11: Machine design for quick change spindles

The designer needs to be very creative and have a different mentality when designing machines. In the testing machine at Plant M, the designer tried to take the idea of "zero changeover" to the extreme by designing a machine that with two spindles in order to have an automatic changeover from one model to another. Instead, Plant L, used a simple pin-hole fixture with one spindle that can changeover in less than minute.

5.3.2 Aircraft Industry

In the assembly plants of aircraft engines, little was observed in the way of changeover from one model to the other with the exception of testing. The problem in an assembly line like the aircraft engine is to have all the necessary tools and fixtures ready to be used at the point of operation. Maintaining the discipline and implementing a 5S program helps to eliminate a great deal of non-value-added time as well as improving the value-added time.

In the fabrication stage, parts like engine casings, rings and seals are suffering from long setup changeovers. Palmer, a part supplier to Company C was visited to learn more about the fabrication of big components like casings and rings. The average changeover time at Palmer is eighteen hours. Changeover or setup time is the time it takes to changeover from part X to part Y and make the first good part Y.

Figure 5-12 shows the current changeover time of an O-ring[+]. The changeover before any improvements took almost 16 hours, where eight hours came from machine downtime. During the 8 hours, the operator waited for a forklift (~45 minutes), looked for fixtures and tools (~33 minutes), part and pallets in the aisles needed to be removed for the forklift to reach the machine (~20 minutes), etc. It was determined that with the design of the new fixture (easy and precise to locate) and elimination of non-value added operations, the machine downtime could be reduced to 10 minutes.

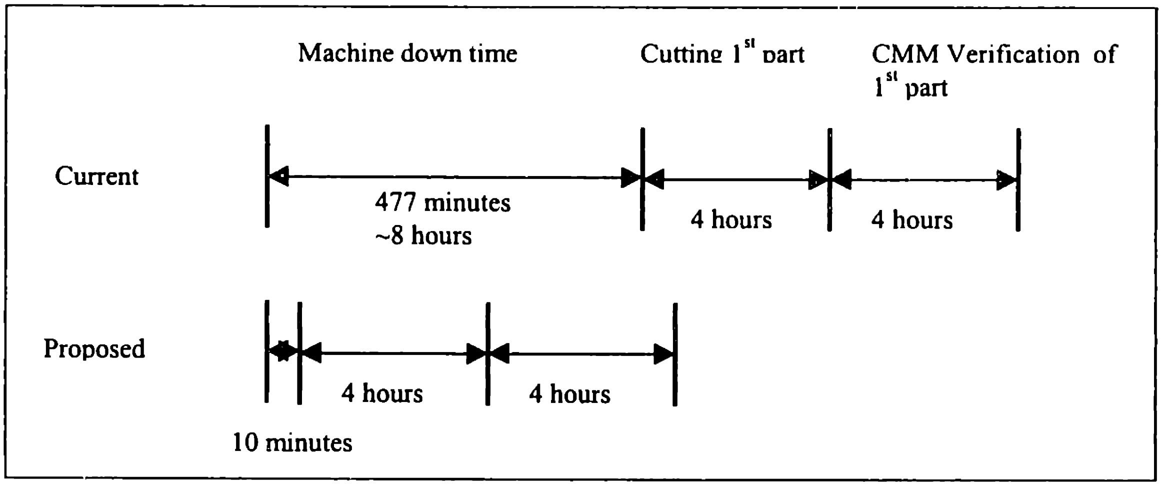


Figure 5-12: Typical changeover at Palmer

Minimizing the setup time is the core of any production system. Without minimal setup times, the production system can not be balanced, leveled, predictable or any of the other design attributes supported by a lean production system. Although setup time reduction is not continuously mentioned in other chapters, it must be clear in the reader's mind that setup time reduction is the foundation of any lean production system.

[+] Study of changeover time at Palmer made by Jose Castaneda, Felipe Varela and Yong Suk Kim

6 Replenishment Time < Demand Interval

Before introducing the Production System Design Decomposition section on replenishment time, a definition of related taxonomy will be given. The essential terms to be defined are order lead time, replenishment time, response time and demand interval. These terms are dependent of different parameters, which are shown in Table 6-1.

Order Lead Time	*f* (administrative time, mfg. Time)
Replenishment Time	*f* ($SWIP_{within\ cell}$, setup time, takt time, qty to replenish)
Response Time	*f* ($SWIP_{between\ cells}$, administrative time, mfg. Time)
Demand-Pull Interval	*f* (distance, customer want/interval)

Table 6-1

The *customer order lead time* is composed of two main processes that we can call P1 (administrative time) and P2 (factory throughput time) (Figure 6-2). P1 is from the time the customer places an order, to the time the work order is released for production. P1 sometimes includes engineering time or any other time that is needed for non-standard products. P2 is the time from the moment the work order is released to the floor to the time the part is shipped to the customer. The main focused of this chapter is on P2. P1 will be discussed in more detail during the case studies in later chapters.

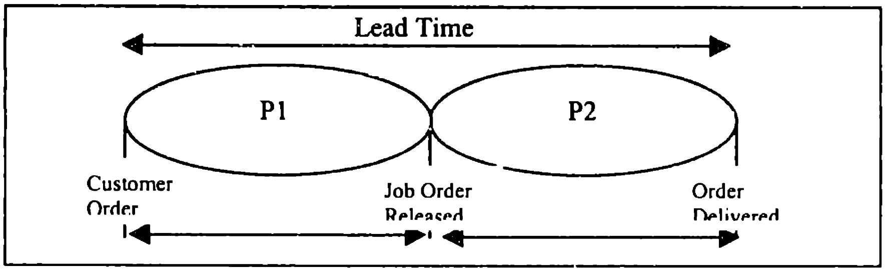


Figure 6-2: Major Processes at any company (administrative/engineering and manufacturing)

Replenishment time is the time it takes the system or sub-system to replenish a container with a standard quantity of parts. Replenishment time is a function of the work-in-process inventory, setup time, transportation of the parts, and time to perform the operations. The replenishment time in a traditional environment can be represented by equation 6.1, where WIP_{i-1} is the work in process inventory (of a *different* part type) in front of Machine i, CT_i is the cycle time of machine or operation i, and C is the container capacity or quantity to replenish. Assuming cycle time is less than takt time and the right amount of standard work in process (SWIP) exists inside the cell, then equation 6.1 can be simplified into equation 6.2.

$$\text{Replenishment Time} = \sum_{i=1}^{n} (\text{WIP})_{i-1} * (\text{CT})_i * (\text{C}) + (\text{setup})_i \qquad (6.1)$$

$$\text{Replenishment Time} = \text{Takt Time} * (\#\text{ of stations}) * 1\text{ part} + (\text{C}-1) * \text{Takt Time} \qquad (6.2)$$

The replenishment time is dependent on the standard work in process (SWIP) available in the sub-system. SWIP is needed to maintain the optimal supply of material (takt time) to satisfy the customer demand (Figure 6-3). If the optimum work in process is not available, then machine can starve and not meet the takt time. SWIP can be calculated using equation 6.3. When the automatic time, load and unload time exceeds takt time or delivery time from supplier, or out of area operations, then a standard amount of work-in-process is needed to create a ‘curtain effect’. More explanation on how to calculate the number of SWIP within a cell is explained in Chapter 9.

$$\#\text{ of SWIP}_{\text{within cell}} = \frac{\text{Automatic time} + \text{load/unload time}}{\text{Takt Time}} \qquad (6.3)$$

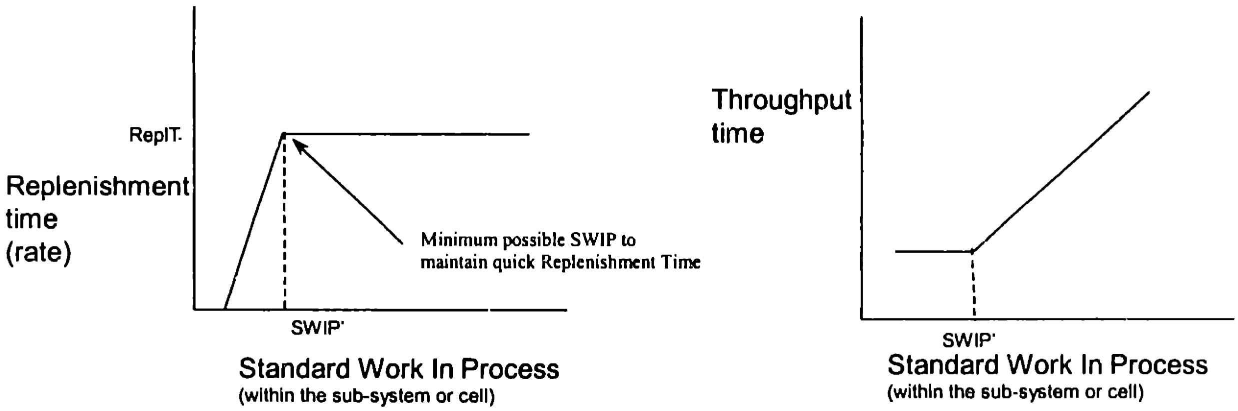


Figure 6-3: SWIP in the cell maintains optimal supply of material

Replenishment time should not be confused with throughput time. The throughput time is the time it takes a part to go from start to finish. While the replenishment time could be only the time for the container quantity to go trough Machine *n* assuming there is enough work-in-process of the same part type before the nth Machine; although this is not the ideal situation.

Response time is how fast a company can deliver a part after a customer has placed an order. In Figure 6-4, the response time is the kanban circulation time (t_{info} + $t_{transport}$) assuming there is standard work in process of each part type between the cells. If there is no standard work in process between cells, the response time is t_{info} + $t_{transport}$ + replenishment time.

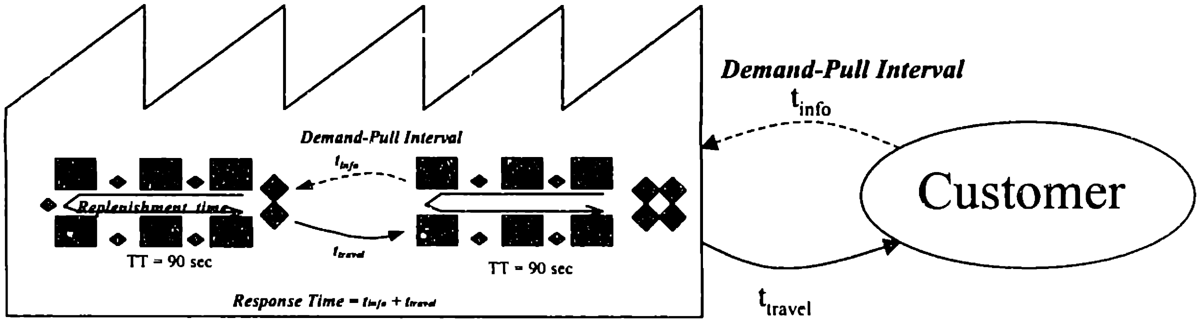


Figure 6-4: Response Time < Demand Interval

A kanban system or having standard work in process uncouples the response time from the replenishment time. Kanban is always trying to minimize the response time with the minimum inventory condition (Figure 6-5). After the optimum level, adding more kanbans or $SWIP_{between\text{-}cells}$ does not add any value to the customer. At this point, the response time is equal to the kanban circulation time. To further minimize the standard work in process, the demand interval needs to be more frequent (shortening t_{info} period) and replenishment time needs to be minimized.

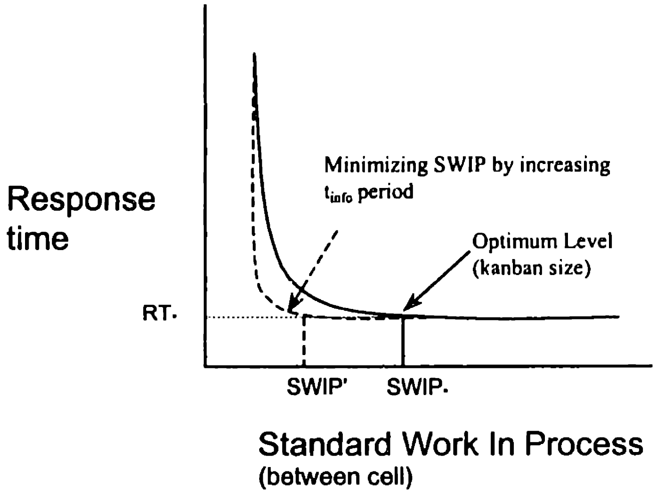


Figure 6-5: Kanban Optimizes the Response Time with minimum inventory

A kanban quantity or how many standard containers should be between two cells can be determined using the following equation:

$$\begin{array}{c}\#\text{ of SWIP}_{\text{between cells}} \\ \text{or} \\ \#\text{ of Production-Ordering Kanban}\end{array} = \frac{\text{Average Dalily Demand*(Lead Time)*(1+safety stock)}}{\text{Container Capacity}} \quad (6.4)$$

Lead time from equation 6.4 is the processing time + waiting time + conveyance time + kanban collecting time, in other words is from the time it takes to replace a kanban. A lead time from ordering to delivery of the supplier kanban is relatively longer than that of the ordinary withdrawal kanban between cells. A notation 'a-b-c' is used for specifying the delivery cycle of the vendor, where 'a-b-c' means that the parts are delivered 'b' times during 'a' days and 'c' delivery time after the order [Ohno, Nakashima, 1995]. That is, the delivery cycle is a/b and the lead time is ac/b [Monden 1993]. The number of supplier kanbans is calculated as follows:

$$\#\text{ of Supplier Kanban} = \frac{\text{Average Daily Demand*(a*c / b)*(1+safety stock)}}{\text{Container Capacity}} \quad (6.5)$$

The *demand-pull interval* in Figure 6-4 is how often a standard container from machining is picked up by assembly, which is correlated to how long it takes assembly to consume a standard container quantity. In other words, the demand interval is the period of demand or frequency of retrieval.

If the replenishment time is less than the demand interval, the standard work in process can be minimized. Right levels of work-in-process inventory and finished goods inventory are needed to uncouple the response time from the replenishment time when replenishment time is greater than the demand interval.

The demand interval not only depends on consumption and customer ordering, but also on how far the producing plant is from the customer plant. The farther the plants are the less frequent the demand interval is due to transportation constrains. At the same time in order to minimize inventories in both plants, the frequency of demand should increase. This relation not only applies from plant to plant but also within the same plant. If the assembly line is far away from the machining line, material needs to be transported via forklift or conveyor. On the other hand, if assembly and machining or assembly and the sub-assemblies are closer together, the operators themselves can move the parts and make retrievals that are more frequent when needed.

6.1 Manufacturing System Design

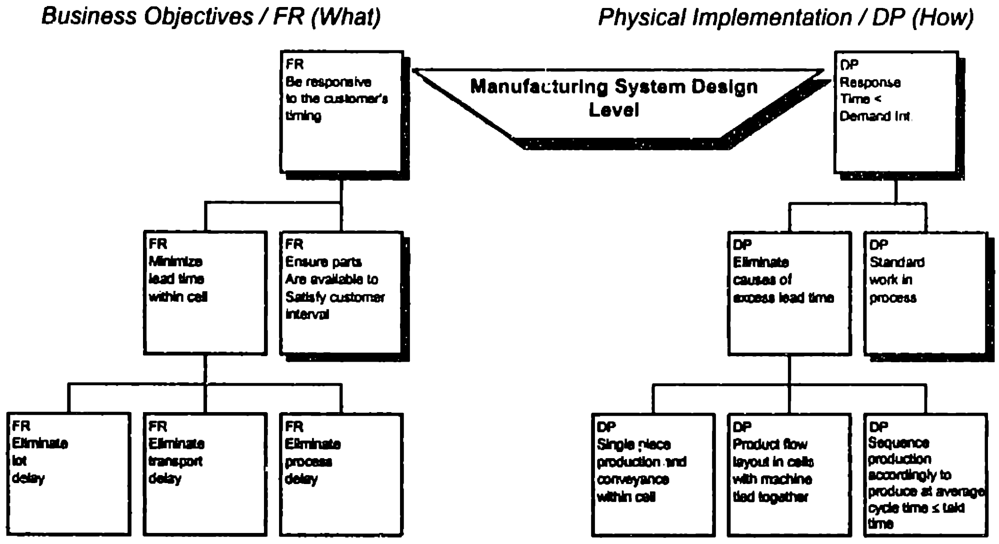
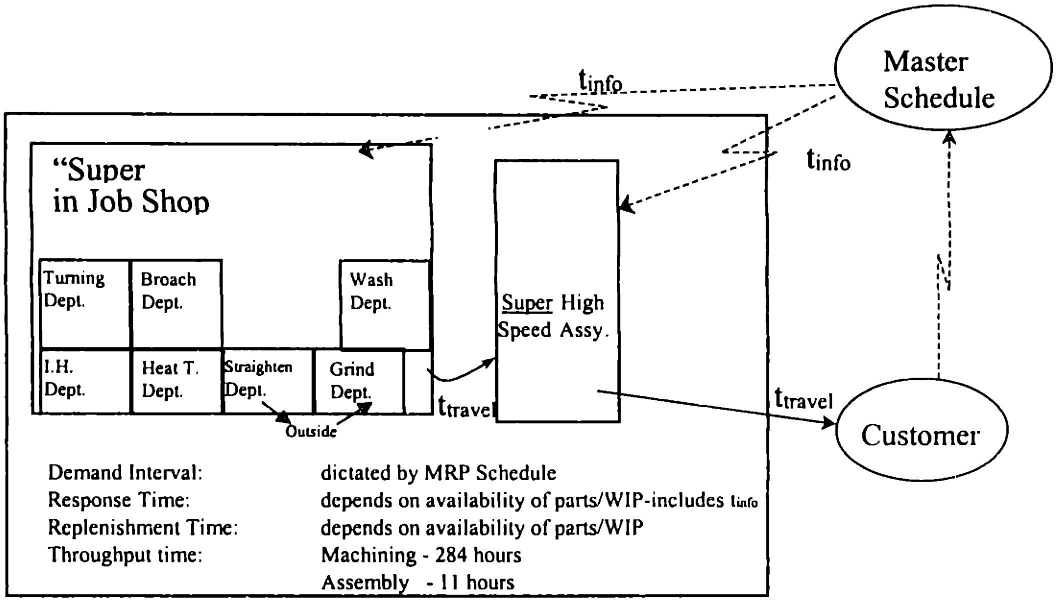


Figure 6-6: Decomposing the requirements and design parameters of the manufacturing system level for having Response Time less than Demand Interval.

6.1.1 Automotive Industry

Figure 6-7 shows a schematic of Plant M design and its relevancy to the taxonomy presented in this section (system level).



Demand Interval: dictated by MRP Schedule
Response Time: depends on availability of parts/WIP-includes t_{info}
Replenishment Time: depends on availability of parts/WIP
Throughput time: Machining - 284 hours
Assembly - 11 hours

Figure 6-7: Plant M Design Integration Result

The customer of Plant M is the vehicle final assembly. Plant M is not very concerned about how often the customer asks for the parts (demand interval). The demand interval is dictated by Plant M's MRP system on a weekly basis. Since production requirements are updated at least once a week, the response time to the vehicle assembly plants can not be less than one week. However, there are 9 shifts of finished goods inventory in order to uncouple the response time from the MRP system. On the other hand, if the part is not in stock it could take as long as 295 hours or 37 shifts to replenish an average daily quantity of 1900 parts (excluding any inventory between machining and assembly). The replenishment time of this system is very dependent on the availability of parts. For this reason there are over 100,000 units of work in process in the machining area with 9,000 units of finished rack bars waiting to be picked up by assembly. It is not easy to know whether the replenishment time can be less or greater than the demand interval neither in assembly nor in machining because of its dependency on parts. One way this company is trying to minimize this unpredictability is by keeping more inventory on hand.

Plant L has a completely different system. One that is more predictable and has a standard work in process just to ensure that the system performs efficiently without many discrepancies. The relevant data at the system level for this company is presented in the Figure 6-8

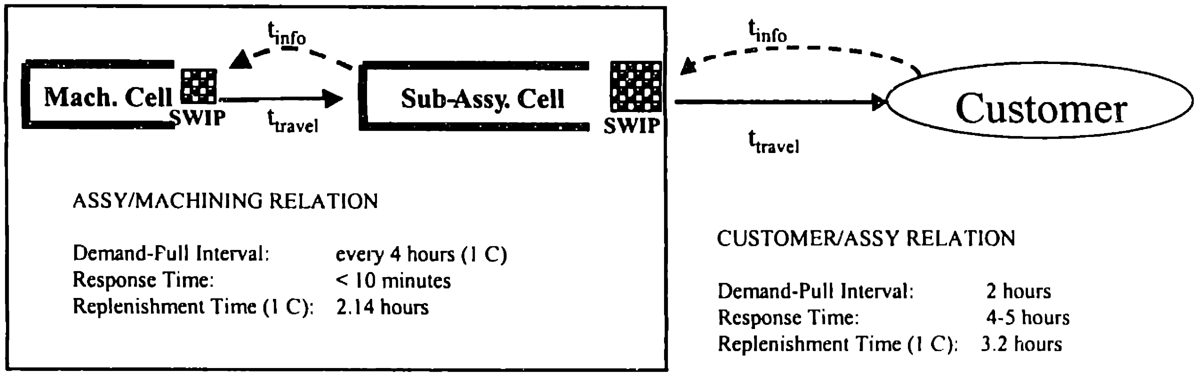


Figure 6-8: Plant L Design Integration Result

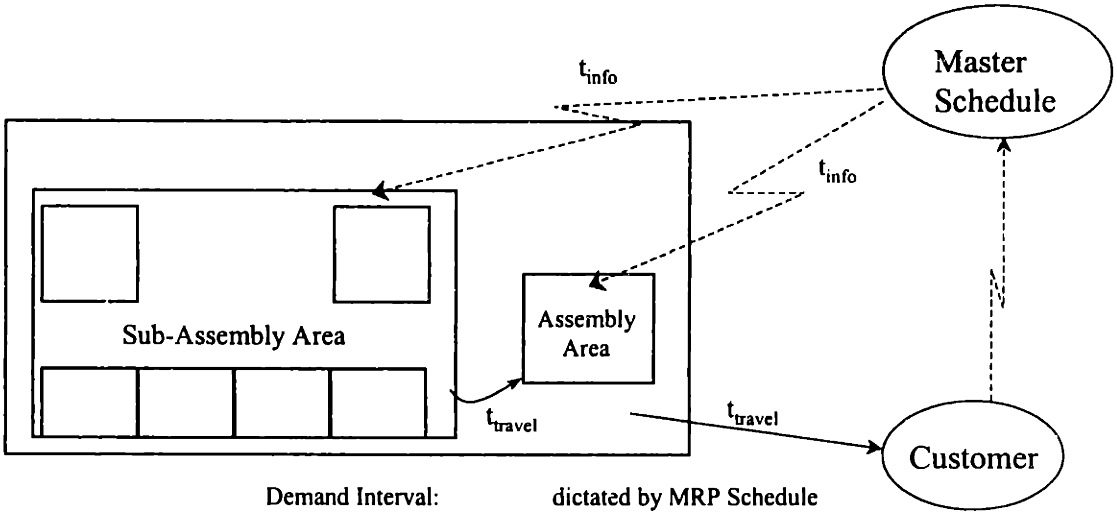
On of the customers of Plant L is picking a standard mix of parts every two hours. The response time to the customer is 4 to 5 hours; that is the time it takes the truck to go from customer to the producer and back. The truck is picking up at least two hours of production from the producing plant (several models). When the truck comes in to pick up parts, it is also leaving the kanban cards or orders for the next day's production. This means that the order lead time is at least one day. In order to uncouple the response time from the order lead time, Plant L has a standard quantity of finished goods (1.5 days) waiting to be picked up.

Inside Plant L, the assembly is demanding a container every 4 hours. The replenishment time of a demanded container is at least 2.14 hours. However, since the machining cell is producing 'shift' requirements, the empty container will have to wait at least one shift. For this reason in order to uncouple the replenishment time from the lead time, there are 8 hours worth of finished rack bars for a given part type waiting to be picked up by assembly. The material handler will come from assembly with an empty container (a cart in this case), leave it in the machining cell and take a full container back to assembly. This takes less than 10 minutes, which in this case is the response time ($t_{info} + t_{travel}$). The response time is very predictable in this case because the kanban system is assuring the correct standard quantity mix of finished goods that will keep the response time minimal.

6.1.2 Aircraft Industry

From the examples given in the automotive industry, it could be seen that there were great differences from one company to the other. Plant M has an unpredictable system with a part dependent response and replenishment time. On the other hand, Plant L has a more predictable system with a known replenishment time, response time and demand-pull interval which are controlled by the customer. The same two scenarios exist in the aircraft engine companies visited.

The interaction of Companies A and B with its customers and the relevancy of the taxonomy presented in this chapter can be represented in Figure 6-9, which contains many similarities to Plant M such as demand interval dictated by MRP, and dependency on parts.

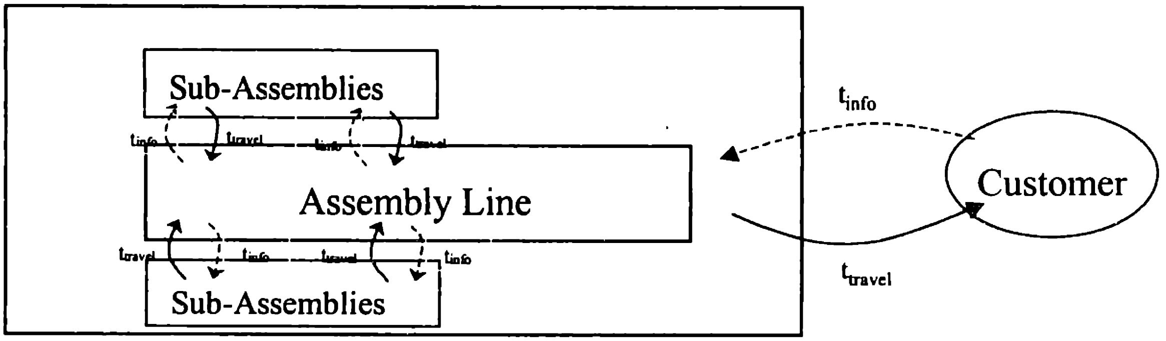


Demand Interval:	dictated by MRP Schedule
Response Time:	depends on availability of parts + t_{info}
Replenishment Time:	depends on availability of parts
Engine throughput time:	25-100 days

Figure 6-9: Representation of Company A and B

Both companies, A and B have a demand interval dictated by the Planning System. The Planning System at both companies, B and A, specifies when to start the engine and how many are needed for a period of time. Once the engine is assembled, it is sent (pushed) to the customer immediately. The response time and replenishment time in these companies is at least a month because of the monthly planning made by the Company's Planning/Control System. In reality it is taking almost half a year due to the backlog that currently exists in the system.

Company C resembles Plant L more closely as seen in the next figure (Figure 6-10).



ASSY/SUB-ASSEMBLY RELATION

Demand-Pull Interval:	Every day
Response Time:	< 10 minutes
Replenishment Time (1 C):	~ 1 day

CUSTOMER/ASSY RELATION

Demand-Pull Interval:	every 2 days
Response Time:	~ 2 days
Replenishment Time (1 C):	~ 1 day

Figure 6-10: Company C, Commercial Aircraft Engine

Company C is able to control efficiently the production of engines in such a manner that they can make the replenishment time be less than the demand interval. The demand-pull interval in this case is two days. A truck is coming into the plant to pick up two engines every other day. Although the throughput time of an engine is less than a month, the replenishment time for one engine is only one day. This disconnection of the throughput time and replenishment time was achieved by implementing a kanban system that links every station in the sub-assembly and final assembly stages. This means that before any station there is a day's worth of production, which translates to one component. Consequently every day the components will move from the preceding station to the subsequent, just like the assembly cell at Plant L but at a slower pace.

6.2 Manufacturing Sub-system Design

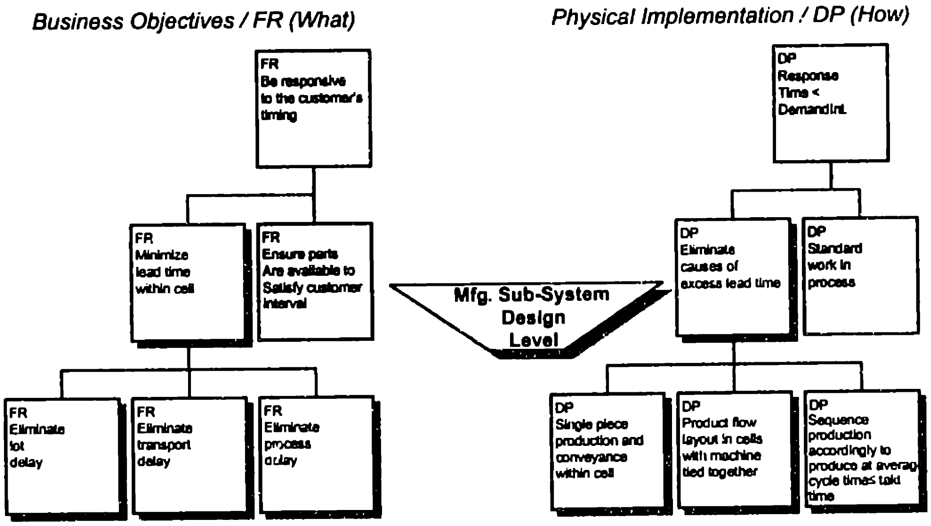


Figure 6-11: Decomposing the requirements and design parameters of the manufacturing sub-system level for having Response Time less than Demand Interval.

The replenishment time under the P2 (manufacturing time) process is strongly related to the trhoughput time. Decreasing troughput time results from the elimination of lot delay, transport delay and process delay [Monden, 1993].

FR: ELIMINATE LOT DELAY
DP:SINGLE PIECE PRODUCTION AND CONVEYANCE WITHIN CELL

Lot delay is caused when batch production is performed. In Figure 6-12, it can be seen that with batch oriented production, the throughput time of 100 parts is 300 minutes. In the batch production, parts sit idle in the preceding process while work is under way on whole batches in the following processes. Every part waits on every other part in the production lot or batch. On the other hand, if single piece-continuous flow is used, then the throughput time is reduced to 102 minutes (Figure 6-12). In single piece-continuous flow, parts are advanced one-by-one between machines. The parts are processed in parallel, not serially in large lots.

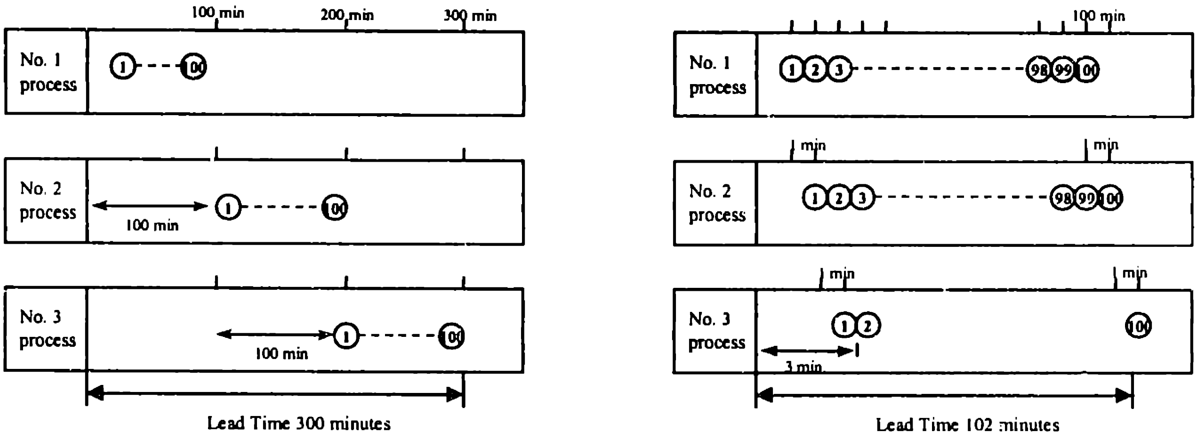


Figure 6-12: Single piece-continuos flow versus Batch "serial" production

FR: ELIMINATE TRANSPORTATION DELAY

DP:PRODUCT FLOW LAYOUT IN CELLS WITH MACHINES TIED TOGETHER

Product flow layout in cell not only helps to eliminate transportation time because machine are closer together, but also makes it easier to control the production. The smaller the production space is for the team leader the easier it is to control. In Figures 2-7 and 2-10 it was seen that for the same production rate, the product flow layout or cell takes half the space in machining because of the operations are contiguous to one another.

FR: ELIMINATE PROCESS DELAY

DP:SEQUENCE PRODUCTION ACCORDINGLY TO PRODUCE AT AVERAGE CYCLE TIME < TAKT TIME

The idea is to level the production not only by quantity but also by time. Takt Time is based on Average Daily Demand[+] and the true production time of the day depends on the man-hours to make a product. To minimize the peaks and vallies of product cycle time which causes delays in the process, the production is leveled in such a manner that the average cycle time is ≤ takt time (Figure 6-13). This means that the sequence must be constructed so that each operation is able to produce its variety of parts within the demand interval of the customer.

[+] Takt Time = $\frac{\text{Available Time}}{\text{Average Daily Demand}}$

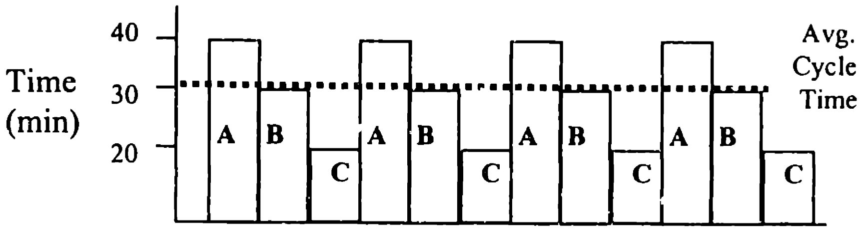


Figure 6-13 : Sequence that enables production within average cycle time

6.2.1 Automotive Industry

According to the decomposition at the sub-system level (Figure 6-11), to eliminate lot delay, single piece flow should be implemented; however in systems like Plant M it is not feasible to implement single piece flow unless a totally new system is designed or the current system is completely redesigned. Currently, Plant M is performing single piece production in most of the machines but batch conveyance. In some areas conveyors have been implemented, but this caused numerous problems in terms of maintenance, reliability and part damage.

Moving the machines together and creating a product flow cell can bring some opportunities for improvement by reducing transportation time and maybe single piece flow can be implemented. Nevertheless, using machines that were not designed for cells are not going to give the true benefits that a lean production system can bring.

Plant L has been using the concepts of single piece-continuos flow production and product flow layout in cells since the company started about 12-15 years ago. Plant L designed the machines and cells to produce one piece at a time and transport the part one by one (within the cell) at a rate less than the takt time.

6.2.2 Aircraft Industry

There is a very good example in the aircraft industry that represents the different generation of sub-systems from a traditional batch-flow department to an aggregation of operations, to an interim cell [Black, 1991] and finally a cell that was designed for single piece flow and faster response time. The different design configurations were taken from different aircraft engine companies all of them producing turbine blades. The comparison presented in this section demonstrates the impact that the sub-system design can make in the system's performance, specifically in the replenishment time needed in this type of business.

Turbine blades (Figure 6-14) are one of the most critical parts in an airplane engine. When the turbine is running, the blades are held firmly in the serration by centripetal force, but the slight freedom to move can provide a useful of damping for unwanted vibration and failure of the engine. For this reason to achieve the necessary manufacturing tolerances at individual serration, the blades must be ground at the serration point and other sections of the blade to create the easy fit in the rim.

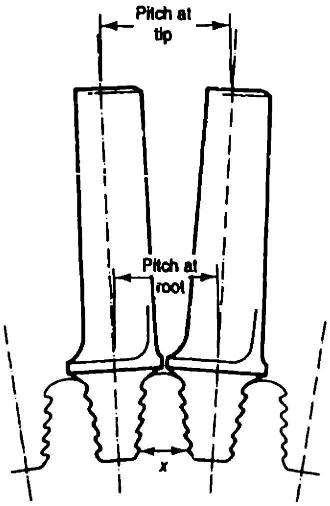


Figure 6-14: "Firtree" root turbine blade

Turbine blades were first processed in a traditional job shop department layout. The first iteration was to group machines together according to product flow. This created a batch flow shop (Figure 6-15), which contained over 20 different manufacturing processes in order to achieve the grinding specifications of a turbine blades and doublet vanes. The production is made in lots that range from 10 to 26 parts with a change over time of at least 8 hours on each machine. The production was based on a monthly requirement and there was more than $5 million finished goods inventory to meet the demand. The throughput time or response time under this sub-system "design" was 32 weeks.

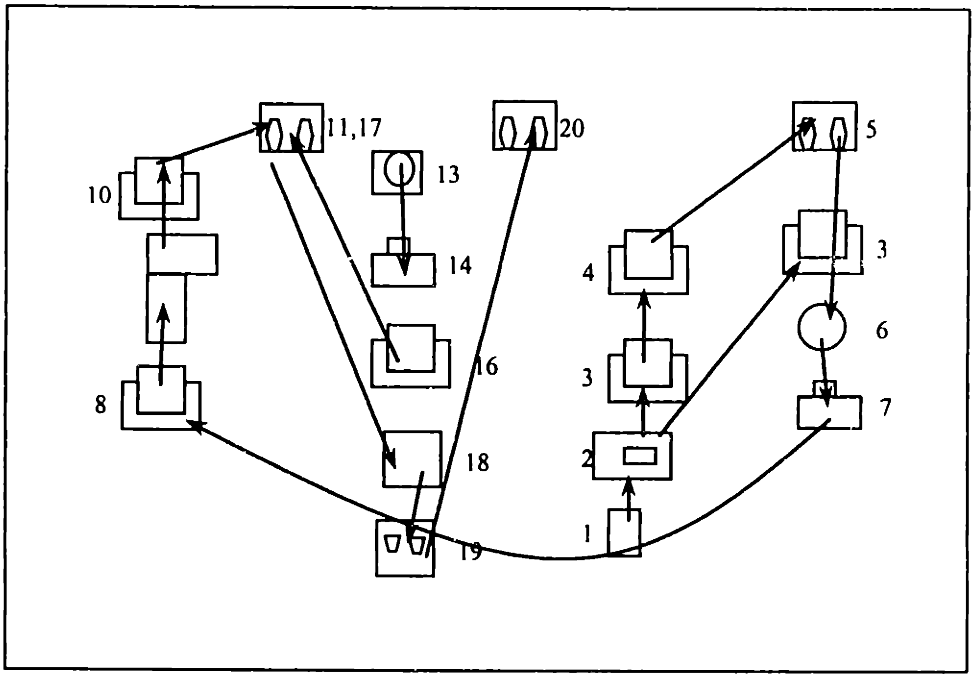


Figure 6-15: Batch Flow Shop

About 10 ago years the aircraft industry saw the need for change to have a sub-system that can produce faster, minimize the labor cost, reduce setup time and produce in what they called "lights-off company". The new design was a $7 million automated "blohm" grinder machine (Figure 6-16) with 12-axes of motion that could grind a blade in 5 minutes. The blade was encapsulated to distribute the force applied to the blade by the grinder. During the design stages, the encapsulation was planned to be used as a reference to the grinding wheel, therefore setup would be minimal. Once in production, the engineers found that there was high variability in the encapsulation surface, consequently it was not accurate to rely on the surface of the encapsulation as a datum or reference surface. To solve this problem, a touch probe device was designed to touch the surface of the blade in more than 50 locations. With all this additional time, the setup continued to be in the range of 8 hours. Since it was very difficult to setup, the machine would run monthly requirements before changeover. The throughput time for one part is in the range of 37 weeks because after the blade has been ground, the encapsulation has to be removed and the blade cleaned. Having a throughput time that long with long changeover times, made the company carry an extra $1 million of finished goods inventory (which is 80% of the total inventory in this new sub-system) to uncouple the throughput time from the replenishment time. The machine is a wonderful piece of engineering, but could not work well in the system it placed.

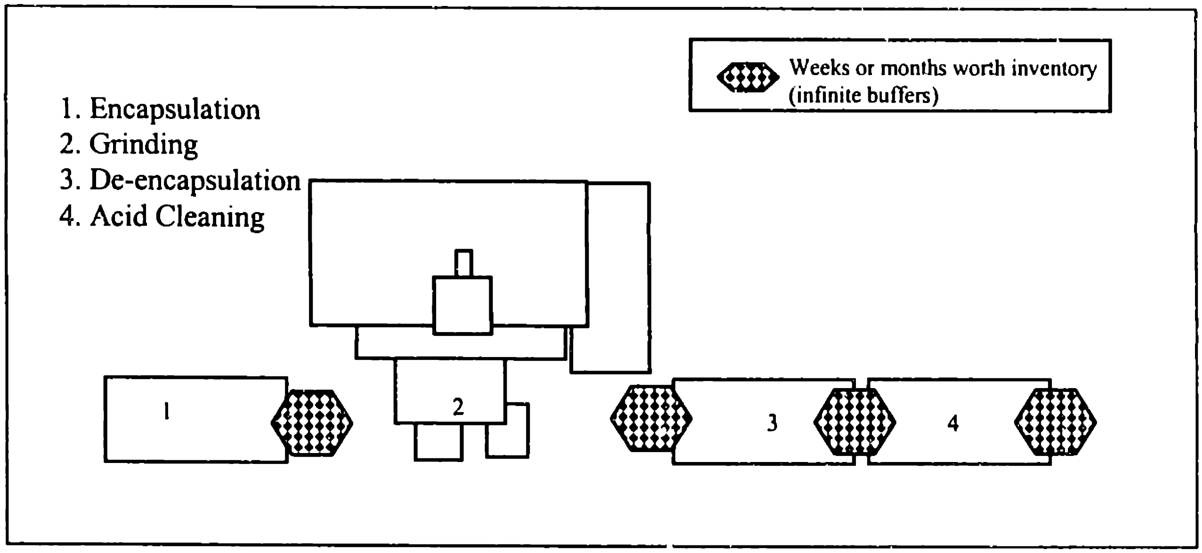


Figure 6-16: Automated Blohm Grinder

Since the production of blades with this Blohm grinder was not cost effective, the same company took three existing grinding machines and placed them in a U-shaped layout (Figure 6-17). This new sub-system has the advantage of subdividing the operations into three machines and creates a more responsive system. Now the lead time, which relates to the response time, was reduced to 18 weeks. The machines used in this cell are simpler 5-axis machines at a cost of $800,000 each. The company was able to reach the same capacity with much less capital investment and operational cost than the Blohm machine. The finished goods inventory in this cell was reduced by to 91%. The run size ranged from one piece in machines 2 and 3 and ten pieces in machine 4. The last machine is running a batch of ten parts at the same time to try minimizing setup time per unit.

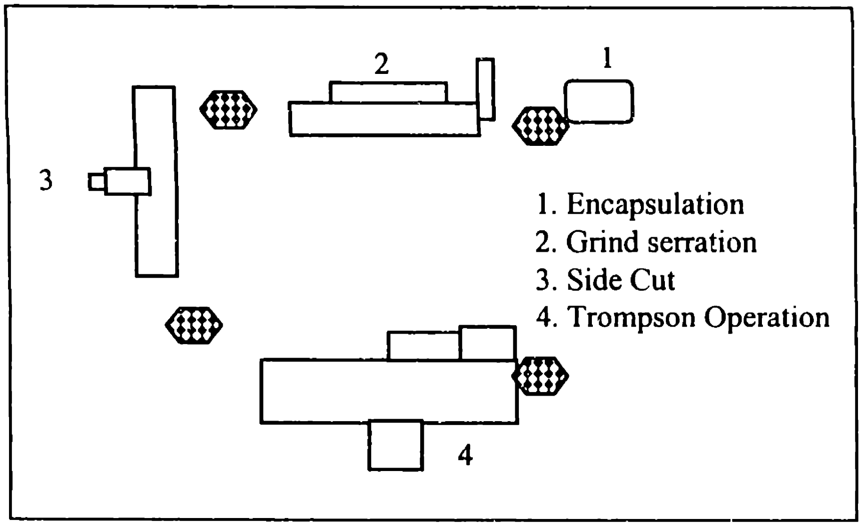


Figure 6-17: "Interim[+]" Cell

The latest generation of conversion occurred in another company where machine processing time were designed to be less than the takt time which enabled separation of worker from machine thereby achieving maximum volume flexibility (Figure 6-18). The grinding of the blades was subdivided into eight operations with the use of simpler, 3-axis machines. The cell is making parts one at a time and has a lead time of 75 minutes. The changeover from one type to another is less than two minutes and can meet daily requirements. All the principles implemented not only gave the company higher flexibility to achieve the demand intervals but also helped the company achieve higher gains in productivity and quality. Even tough the cell is producing for two customers, it can manage very effectively the response time for each customer and have a minimum replenishment time.

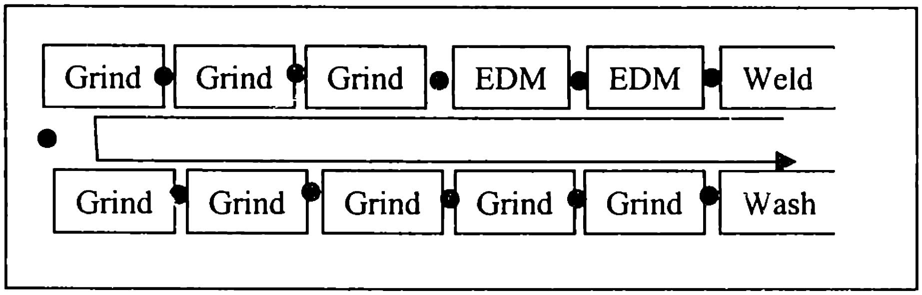


Figure 6-18: Lean Blade Grinder Cell Layout [Womack, 1996]

[+] J.T. Black defines interim cell as existing machines in a U shape layout

7 Predictable Time and Quality Output

The key to keeping the customer satisfied is having a predictable flow through the line. In particular the cycle time variability must be minimized. If the cycle time variability is low, then we know with a high degree of certainty how long it will take a job to go through the plant. This allows the company to quote more accurate due dates to the customer. The most common sources of variability in manufacturing environment are:

- material, operators variability
- machine breakdown variability
- setup variability
- material defect/rework variability

The focus of this chapter is on the variations that can occur within the manufacturing system; therefore, factors such as volatility or seasonal demand, weak interaction with suppliers and economic factors are not consider in this chapter.

This chapter categorizes the sources of variability in two major categories: variability due to time differences (operator, man, machine) and quality (Figure 7-1). Both categories are closely related because when quality of the part is not within specifications, then the throughput time will increase; however, to minimize variation from each group different design choices need to be made. Predictable time output is analyzed at the sub-system level and is primarily dependent on the standard work and availability of parts. On the other hand, predictable quality deals with prevention and detection of defects and is analyzed at the machine/operations level.

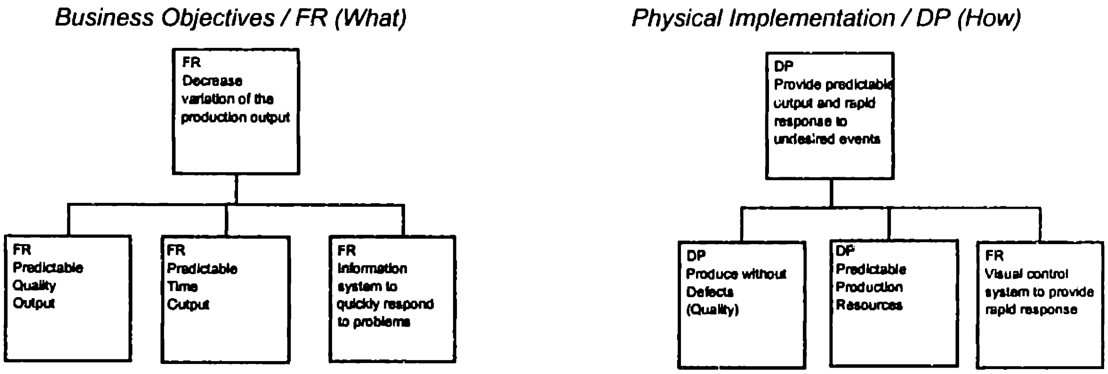


Figure 7-1: Predictable time and Quality Output to Decrease Variation.

Contrary to previous chapters, the examples in the sections to follow are not subdivided into aerospace and automotive because the examples in this chapter can be generalized for both industries.

7.1 Predictable Time Output

A manufacturing system's output is completely dependent on its production resources. This section will cover three main resource components needed to create a time predictable output. Resource components are categorized into material availability, worker operational time and machine processing time.

7.1.1 Manufacturing Sub-System Design

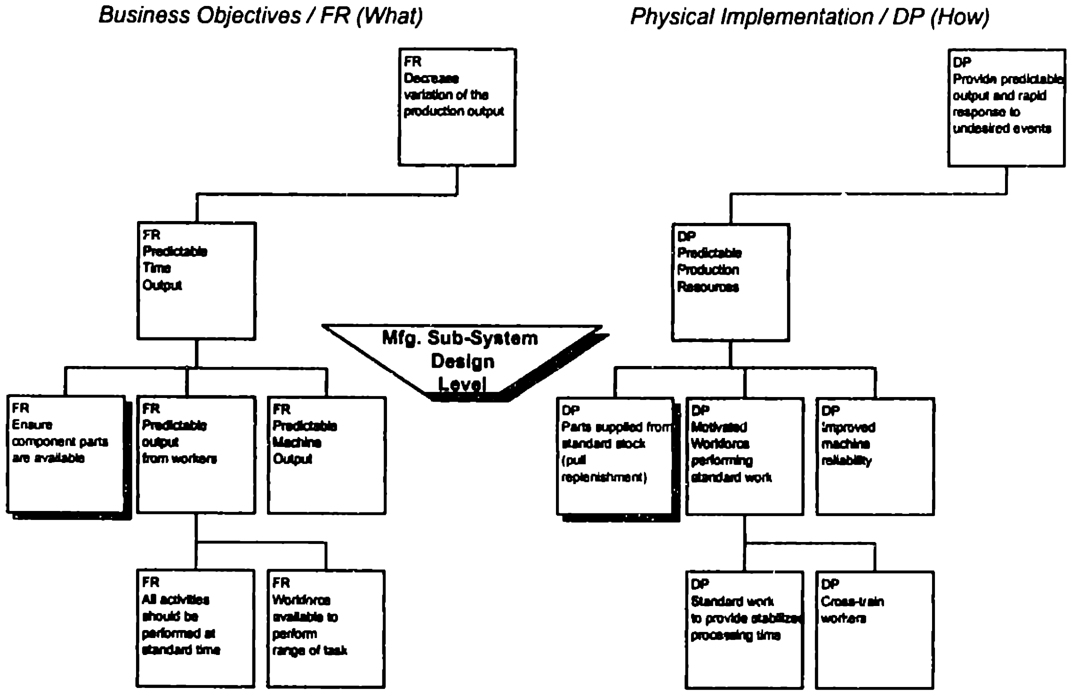


Figure 7-2: Predictable Time Output-Manufacturing Sub-System Design Deomposition

At the sub-system level, the focus is on ensuring the availability of parts to keep the line producing at the customer demand rate. A part shortage could create a complete stoppage of the production line and in many instances a deviation from standard work instructions (work-around). Deviating from the standard work not only causes variation in time, but also increases the probability of making mistakes and creating defective products. For example, in Company B, when a part or component is not available, a "dummy" part is placed on the assembly until the needed part arrives. In some instances the sequence of events will be alter causing the operator to perform steps that he may not understand or may not be familiar consequently missing important steps during the process. There is also the possibility of inadvertently causing damage that is not detected which could be a latent defect.

From the aircraft engine study, part shortages were found to be the biggest cause for engine throughput variation. For example, Company B has a normalized (actual/planned) build time that ranges from 1.5 to 16 and 70% of the extra time was due to part shortages. In any given day, Company C would have an average of 18,000 parts delinquent[+] or late. On the other hand, Company C has a very predictable output with minimal variability in the build time of the engine (normalized build time ranges from 0.8 to 1.8). It was found at Company C that 97% of the time parts were available when starting the engine assembly. The engine will not be released to the floor until all parts needed are in the plant. This occurs only 3% of the time.

There are two activities that must be done concurrently to solve the problem of part shortages. One is the implementation of a pull system (*DP: Pull Replenishment*) to ensure that the right quantity and type of parts are available when needed and the second one and most important is integrating the supply chain. However, before telling suppliers to fix their problem and synchronizing to the producing plant, the producing plant should establish a more predictable output. A kanban or pull system achieves less variable cycle times than does a pure push system. Since cycle time increases with WIP levels (Little's Law[•]), and kanban prevents WIP explosions, it also prevents cycle time explosions. Chapter 9 shows in more detail how to determine kanban sizes.

[+] Site visit and interview with Plant Manager

[•] Little's Law: TH = WIP/CT. Throughput time = work-in-process inventory/cycle time

7.1.2 Machine-Operation Design

At the machine-operation design level, a predictable output is dependent on the worker operations and the machine reliability.

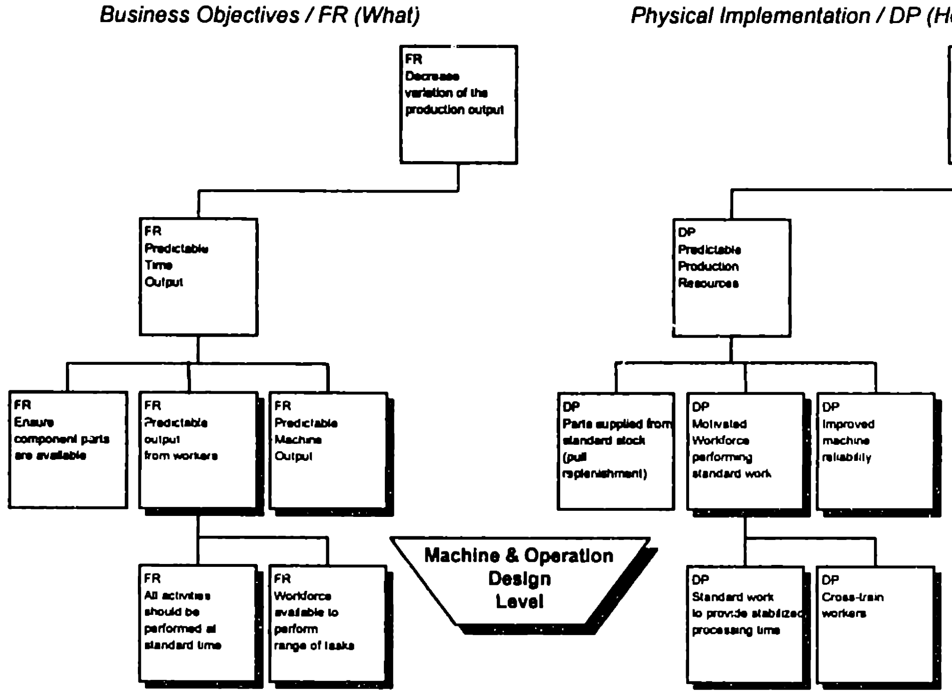
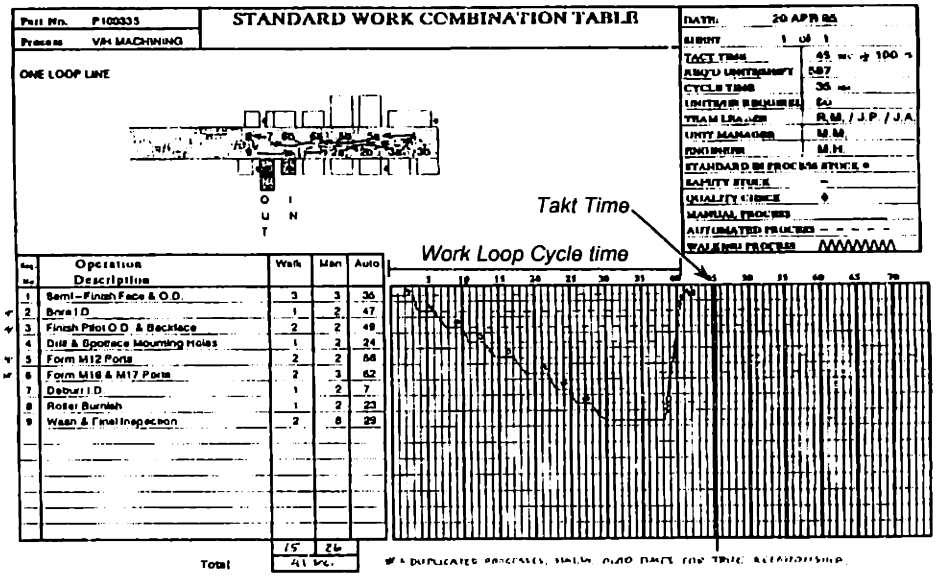


Figure 7-3: Decomposing the requirements and design parameters of the machine/operation level for having a Predictable Time Output

In Chapter 4, *Balance Production*, we saw that work loop cycle time is one of the most important control variables of the cell cycle time. The work loop cycle time is completely dependent on the worker and its interface with the machines since the work loop cycle time = manual time + walking time. For this reason to minimize the variability in output and cycle time, the worker's tasks (manual operations) must be standardized and tools must be designed to ensure that the operator performs the sequence in a standard manner. This means that different operators should perform operations in the same amount of time and in the same fashion to minimize product time variability.

A standardized operation not only help minimize variability and production time output, but also helps enhance system's flexibility. That is, creating standardized operations help cells achieve the ability of changing capacity in small increments by adding or removing operators when needed. When operations are standardized, an extra operator coming from another department or cell should be able to complete the operations in the same amount of time as any other 'regular' worker in the cell. Perhaps the standardization of operations will minimize the learning curve effect by making the operations simpler and easier to repeat.

A tool that helps in achieving standardized operations is the standard-work-routine sheet. The standard work routine sheet is a tool designed to show the passage of time at a glance to help in the determination of work sequence and standardization of operations. It contains information on work sequence, work content and operations time (Figure 7-4). The foreman/team leader must follow the standard operations routine sheet and do the work himself. He must certify if he can do a good job in the sequence within the cycle time given. Once the team leader can perform the standard operations well, he must teach those operations to his workers until everything is fully understood.



STANDARD WORK COMBINATION TABLE

Part No.	P100335
Process	VH MACHINING
Date	20 APR 95
Shift	1 of 1
Takt time	45 sec ÷ 100 %
Req'd units/shift	587
Cycle time	35 sec
Team leader	R.M. / J.P. / J.A.
Unit manager	M.M.
Engineer	M.H.
Standard in process stock	●
Safety stock	–
Quality check	◆
Manual process	———
Automated process	– – – – –
Walking process	ΛΛΛΛΛΛΛ

ONE LOOP LINE

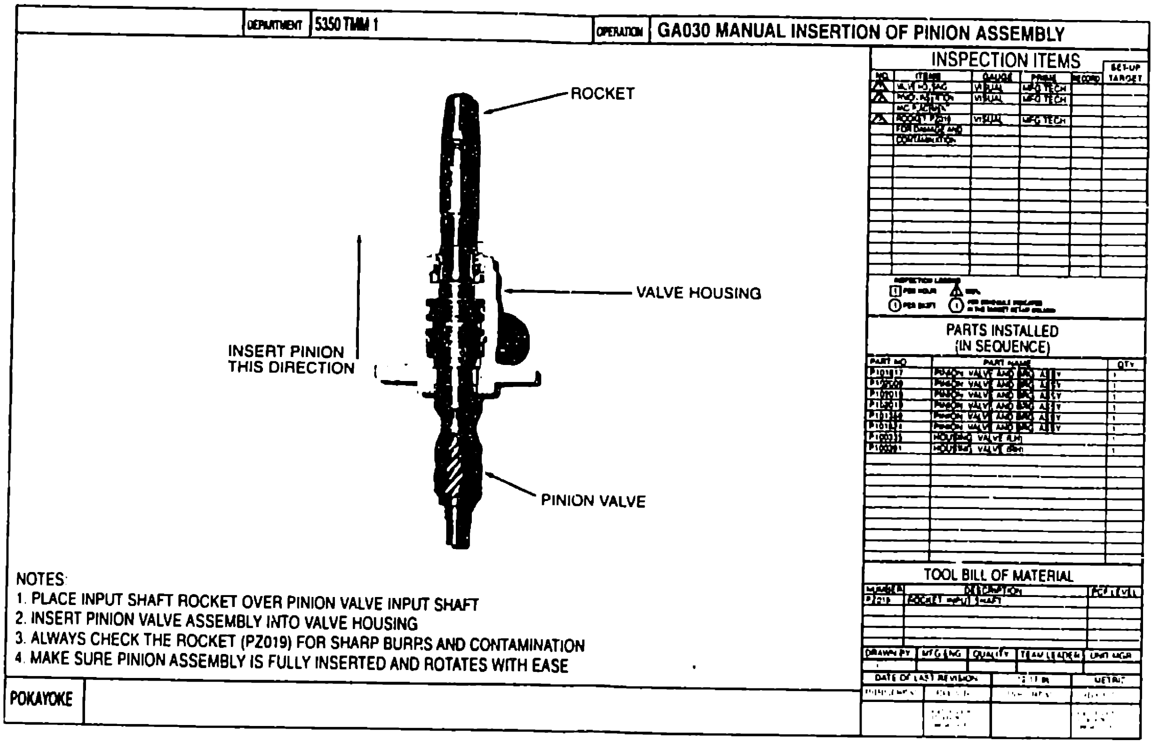
No.	Operation Description	Walk	Man	Auto
1	Semi-Finish Face & O.D.	3	3	36
✱ 2	Bore I.D.	1	2	47
✱ 3	Finish Pilot O.D. & Backface	2	2	49
4	Drill & Spotface Mounting Holes	1	2	24
✱ 5	Form M12 Ports	2	2	66
✱ 6	Form M16 & M17 Ports	2	3	62
7	Deburr I.D.	1	2	7
8	Roller Burnish	1	2	23
9	Wash & Final Inspection	2	8	29
Total		15	26	
		41 sec.		

Figure 7-4: Standard Work Routine Sheet example from Plant L

The most important aspect in maintaining a continuous predictable output with standardized operations is cross training of operators and maintaining strict discipline in the operational sequence. Every operator must be trained within the cell first and then ideally within the manufacturing system. The operations must be standardized to the level of human motion. The next example demonstrates the level of detail that Plant L is doing when standardizing operations:

> "*Remove Rack Housing from container with right hand, gripping around crimped area. Remove rack housing from washer, place onto tray, place unwashed rack housing into washer with yoke hole fitting against plate. Hit start switch with right hand. Remove pressed rack housing oil seal from container and place onto press head with spring facing down. Place rack housing in press. Hit switch with right hand. Remove pressed rack housing and place on conveyor. Place bearings on press heads. Put rack housing into press machine with mounting face down. Hit start switch with right hand.*" [Plant L Standard Operation Handbook]

All the operations described above are made by one operator in less than 70 seconds (takt time). In situations where high volume cells are not used (i.e. aircraft engine assembly), the same principle of standardizing operations must be used. The standard work routine sheet (SWRS) or other methods for demonstrating standard operations should be used. For example, a hybrid of the SWRS can be a pictorial one, where there are several pictures demonstrating how the process should be done (Figure 7-4). These sheets need to be on the floor at all times and easy to access by the operators. Some companies have computer terminals in every station to digitize the work standard routine sheet. The digital method is elegant; however it is an expensive method, which does not create an incentive to continuously improve.



DEPARTMENT 5350 TMM 1

OPERATION GA030 MANUAL INSERTION OF PINION ASSEMBLY

INSPECTION ITEMS

NO.	ITEMS	GAUGE	[illegible]	RECORD	SET-UP TARGET
[illegible]	[illegible]	VISUAL	MFG TECH		
[illegible]	[illegible]	VISUAL	MFG TECH		
[illegible]	ROCKET [illegible] FOR DAMAGE AND CONTAMINATION	VISUAL	MFG TECH		

PARTS INSTALLED (IN SEQUENCE)

PART NO	PART NAME	QTY
[illegible]	PINION VALVE AND BRG ASSY	1
[illegible]	PINION VALVE AND BRG ASSY	1
[illegible]	PINION VALVE AND BRG ASSY	1
[illegible]	PINION VALVE AND BRG ASSY	1
[illegible]	PINION VALVE AND BRG ASSY	1
[illegible]	PINION VALVE AND BRG ASSY	1
[illegible]	HOUSING VALVE [illegible]	1
[illegible]	HOUSING VALVE [illegible]	1

TOOL BILL OF MATERIAL

NUMBER	DESCRIPTION	[illegible]
[illegible]	ROCKET INPUT SHAFT	

DRAWN BY	MFG ENG	QUALITY	TEAM LEADER	UNIT MGR

DATE OF LAST REVISION

METRIC

NOTES:
1. PLACE INPUT SHAFT ROCKET OVER PINION VALVE INPUT SHAFT
2. INSERT PINION VALVE ASSEMBLY INTO VALVE HOUSING
3. ALWAYS CHECK THE ROCKET (PZ019) FOR SHARP BURRS AND CONTAMINATION
4. MAKE SURE PINION ASSEMBLY IS FULLY INSERTED AND ROTATES WITH EASE

POKAYOKE

Figure 7-4: Example of an Operations Method Sheet

7.2 Predictable quality output

In a continuous flow factory, there is no conflict between quantity and quality. Quality always prevails. There should be no flow unless quality parts are being produced. This philosophy represents the major difference from the common practice of producing poor quality and fixing it later. Managers must make quality the number one priority and give the authority to workers of stopping the line if any problem or defect is being produced. When production is stopped, all resources must act immediately to solve the problem

The definition of a defect is a part that fails to conform or perform to a desired requirement or purpose. The best method to improve quality or to build quality parts from the beginning is to find a design that is so robust that parts meet the functional requirements despite variation in the processes. However, that ideal situation is not feasible in almost every case where manufacturing is involved.

In practice, quality problems are one of the principal causes of variability. Additionally, by causing work to be done over (rework or replacement for scrap parts), quality problems often end up increasing the utilization of workstations. By affecting both variability and capacity, quality problems can have extreme logistical consequences [Spearman, Hoop, 1995].

To achieve high quality yields, the machines and equipment must be capable, but most important, the defects must be detected to eliminate further defects in downstream operations and ultimately, prevented from happening. For this reason the next section focuses on the understanding of possible design objectives at the machine/operations design level.

7.2.1 Machine/Operation Design

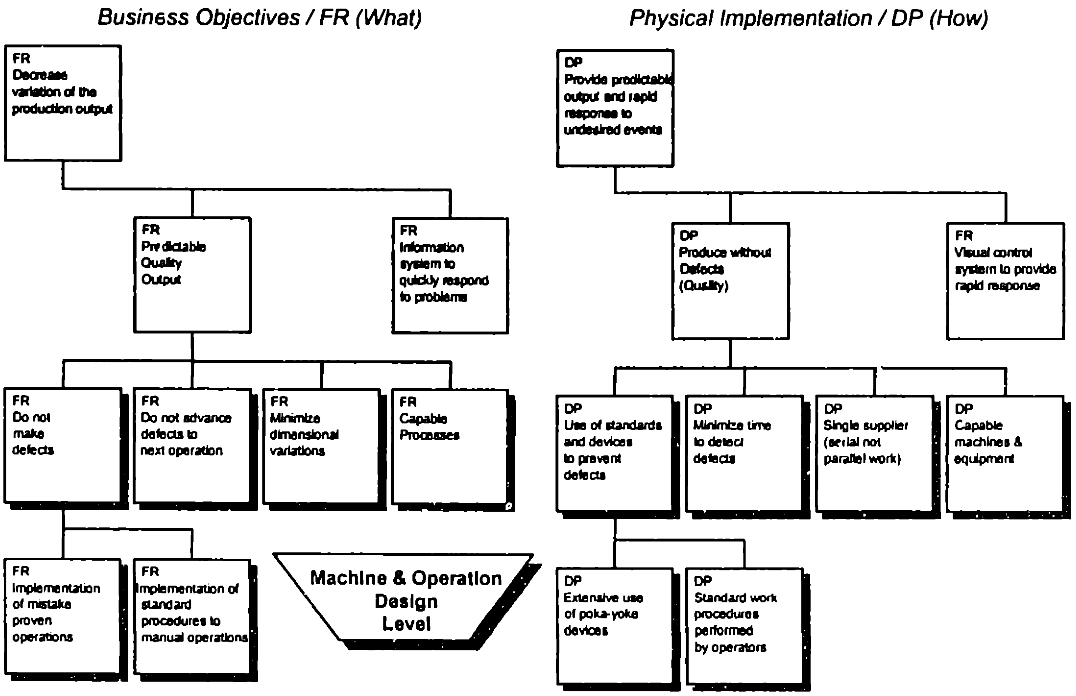


Figure 7-5: Predictable Quality Output-Machine/Operations Design Decomposition

Although four main design parameters are described in the decomposition as to design approaches to "*Produce without defects*", the emphasis will be on "*Use of standards and devices to prevent defects*", and "*Minimize time to detect defects*". The element, "*Capable machines and equipment*" is a fundamental requirement of any manufacturing process and it is not discussed in this chapter. The production of “*serial and not parallel*” is just trying to minimize variation that exists from machine to machine. For example, consider a department with three similar machines where the same part is processes in parallel. All the machines can have the same Cpk's (figure 7-6) however because the variance is significantly increased by the spread in the three means, the overall Cpk of the department is reduced.

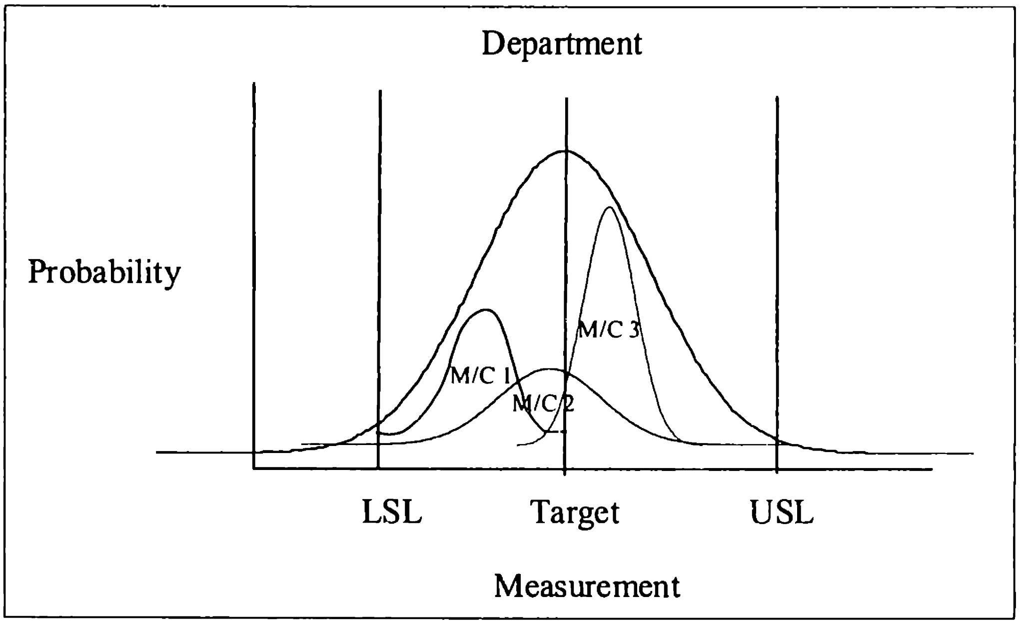


Figure 7-6: Variance Significantly Increased by the Spread in the Three Means

One way to *minimize the time to detect defects* (during which more defects are often made) is by implementing more inspections right after every process. However, the cost of inspections including labor (inspector's wages), capital for inspection tools, and lost revenues as a result of increased cycle time makes it economically unfeasible to have a quality inspector inspect all parts after each operation. Some methods to reduce the inspection costs allow inspecting a small portion of the parts and deducing the quality of the rest (Statistical Process Control). The problem with this is that it is possible for a defective part to slip through, all the way to the customer. Clearly if one wants to have only defect free products leave the factory, 100% of parts must be inspected.

The solution to the inspection cost and time should not be to replace inspection with statistics. The solution is to reduce the time required for each inspection, as well as increase the number of inspections that can be done by the operators themselves. In this manner, the cost of inspecting 100% of the parts can be reduced to a feasible level. An added benefit is that if one can detect problems immediately after they occur, the company can save money on rework (or even warranty work), so that these inspections will actually pay for themselves as well as prevent defective products from reaching the market.

Even better than minimizing the time to detect defects, it would be better to prevent any defects from happening ("*use of standard and devices to prevent defects*"). Preventing defects could be done with the design of devices (poka-yoke) that can shutdown the machine or equipment before any defect is created. Standard procedures/operations, like the ones discussed in the previous sections, can also minimize the chance of creating a defect.

A poka-yoke possesses two functions: it can carry out 100 percent inspections and, if abnormalities occur, it can carry out immediate feedback and action [Shingo, 1986]. The defects which are the easiest to prevent using Poka-Yoke devices are the following:

- defects due to incorrect fixturing of parts
- defects due to excessive requirement applied (i.e., excessive travel of machine head, excessive torque applied to bolt, etc)
- defects of forgetting to add certain parts (either nuts, washers, seals, bolts, or other small items, including pan stock parts)
- improper alignment of a part during assembly

Plant L has implemented poka-yoke devices in most machines and operations performed in machining as well as assembly. By doing so, they have been able to even detect defective parts coming from the suppliers without doing major inspections when material comes to the plant. Figure 7-7 demonstrates some results from designing and applying the poka-yoke devices. Even though Plant L is receiving on the average 2,000 ppm (defects per million) from their suppliers, there are only 61 ppm on the average reported by their customers. Out of the 61ppm, 15-25 percent of the root problem is defective parts from suppliers. Some of the poka-yoke designs used in Plant L will be presented in the next section.

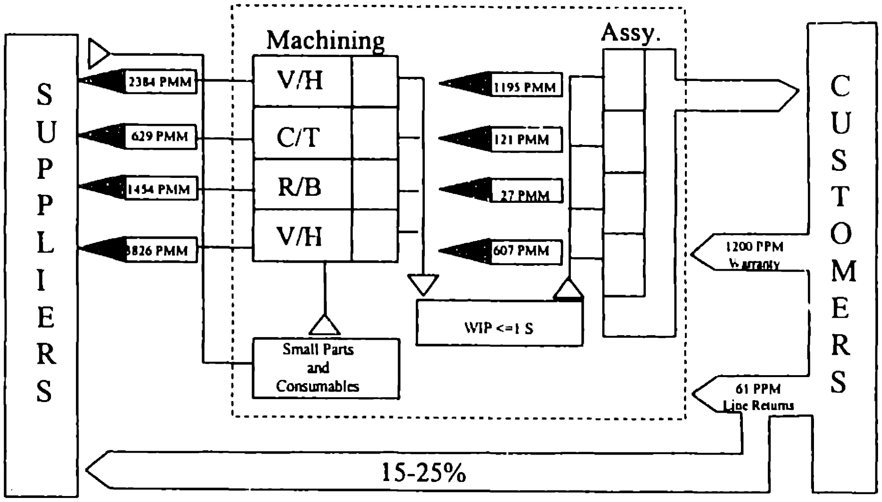


Figure 7-7: Results at Plant L from Implementing Defect Prevention and Detection Devices in all Operations

In another company where air bags are manufactured, the company went from almost 1500 PPM to 15 PPM in less than 4 years, with the same machines and equipment. The difference is that every machine in the fabrication and assembly lines contains several poka-yokes. The company bought standard machines designed the poka-yoke devices internally. Figure 7-8 shows an example of a typical machine in this company. All machines are manual at this plant, and most of them are sewing machines.

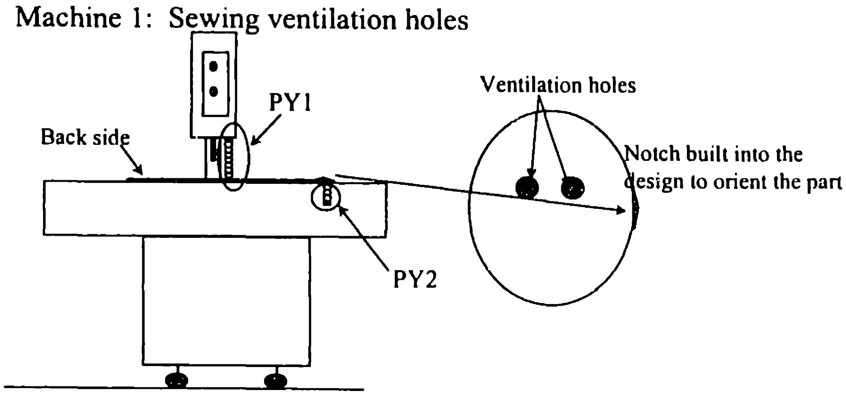


Figure 7-8: Poka-yoke in air-bag sewing machine

In the assembly cell at Plant L the most common poka-yoke is the light curtain to detect that the operator has performed the correct operation and/or taken the right amount of parts. Once the operator's hand obstructs the transmission of light, the poka-yoke is triggered. The steering gear will not move from the station until all poka-yokes from that stations have been triggered.

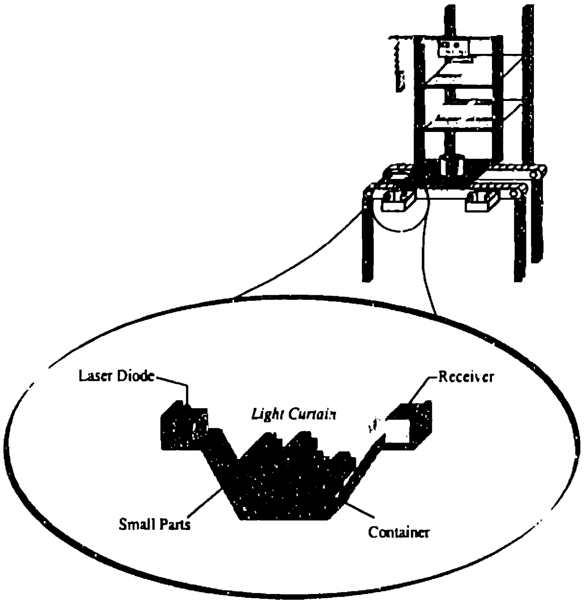


Figure 7-9: Typical Poka-yoke Device to Detect if Parts were taken by Operator

The second most common poka-yoke is designed in the machines to detect that the part has been successfully assembled (Figure 7-10). For example during the bearing/seal pressing operation, the press shaft has a hole, which is connected to a pressure sensor. The pressure sensor detects a pressure change when the part is placed on the shaft. When the shaft is lowered and the seal is placed on the surface of the housing, an induction sensor detects the position of the shaft and stops the shaft from continuing to apply downward force.

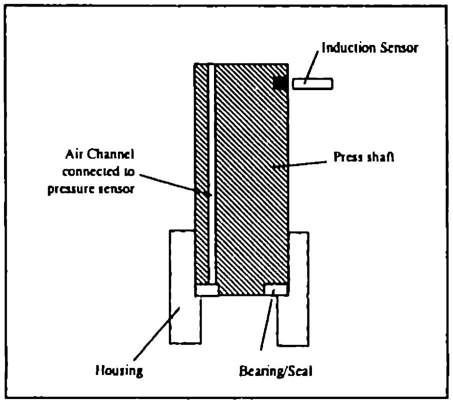


Figure 7-10: Typical Poka-yoke used to detect if Part has been Placed Correctly

Poka yoke devices are the key technology used in the Toyota Production System to achieve the high quality / low cost products demanded by customers. The design of poka-yoke devices must be included in any process that deals with the design of machines or stations that are interfaced to operators. In the next chapter, a methodology for implementing a lean production system is developed and one step is dedicated to the development of poka-yoke devices. Some decision steps are presented to help and guide the designer of poka-yokes.

8 Methodology for Implementing Lean Production Systems

In this chapter a methodology for designing new manufacturing systems or converting existing ones to system that uses the principles of lean manufacturing will be developed. The methodology to be used for designing a new system is different from the one used to convert an existing system. This methodology will point out these differences and create tools to be used during the implementation stage. Some of the steps in the methodology will create the necessary metrics to measure the performance of the system. There are some differences to the approach taken when implementing assembly and machining systems. Both cases are developed in this chapter.

8.1 Overview of Methodology

Improving existing production systems or designing new production systems consist of the participation of other areas in the Enterprise and Value Chain. In the previous chapters, the emphasis was given to Production System Design only; however, when designing new or converting existing manufacturing system other disciplines must be included during the improvement process. Figure 8-1 demonstrates the interactions of four major disciplines needed for the design of new or existing manufacturing systems.

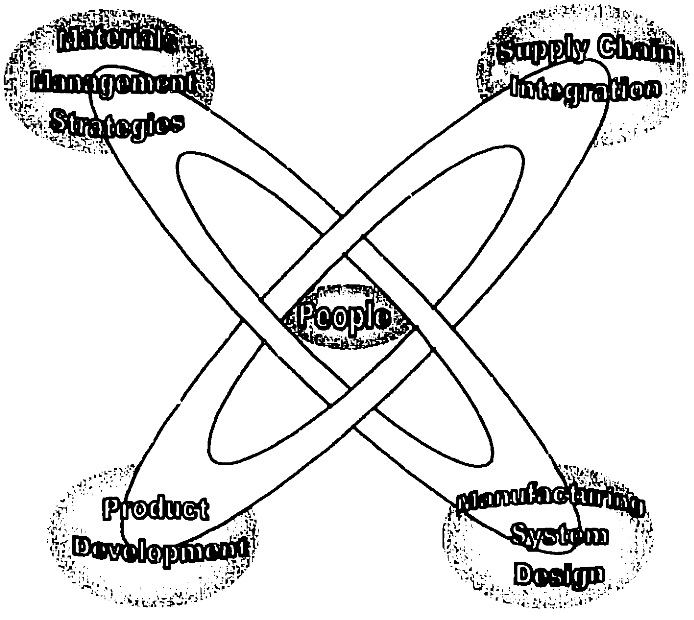


Figure 8-1: Manufacturing System Design must be supported by other disciplines

The Production System Design elements described in the PSDD (Figure 2-1) are defining the elements needed for the Manufacturing System Design and elements concerning Materials Management Strategies within a plant. However, the implementation of a production system must be supported by the integration of the supply chain, and product development. As seen from the figure, the design and implementation process must be a people-centered action. Direct and indirect labor and any other stakeholder of the manufacturing system must be actively involved during the design and implementation process of the system. People enjoy their work when it involves trying out their own ideas, mastering new skills, and making a visible contribution [TMC, 1992].

Integrating the supply chain has demonstrated an increase in benefits when converting to a lean production system. When improving an existing system, it is necessary to have full participation from suppliers in order to minimize volatility and variability of parts being delivered. Toyota believes in the full participation of its suppliers. For this reason, Toyota created a group called the Toyota Suppliers Group, which is in charge of disseminating the Toyota principles throughout suppliers of Toyota's assembly plants in North America.

Supplier involvement is not only important for part-logistics, but also in the early stages of product development. Many researches have concluded that suppliers play a vital role in product development (Iman, et al., 1985). Linker, et al. (1995) provide a concise summary of current literature on Japanese supplier relations [Sobek, 1997]. Japan tends to outsource more engineering work (Figure8-2), using a strategy called 'black-box', where the customer gives the supplier certain design requirements and the supplier designs a part or subsystem to meet the requirements. Figure 8-3 shows the relation of black-box parts made by suppliers versus detailed parts and proprietary parts in three different regions of the world. Black-box sourcing results in more parts tailored to a particular product. This 'black-box design' idea helps the customer and the supplier. The customer benefits from a reduction in development cost and time by outsourcing engineering hours to the suppliers. At the same time, the supplier designs a product that could be manufactured according to existing machines and equipment, thereby minimizing its internal cost of production.

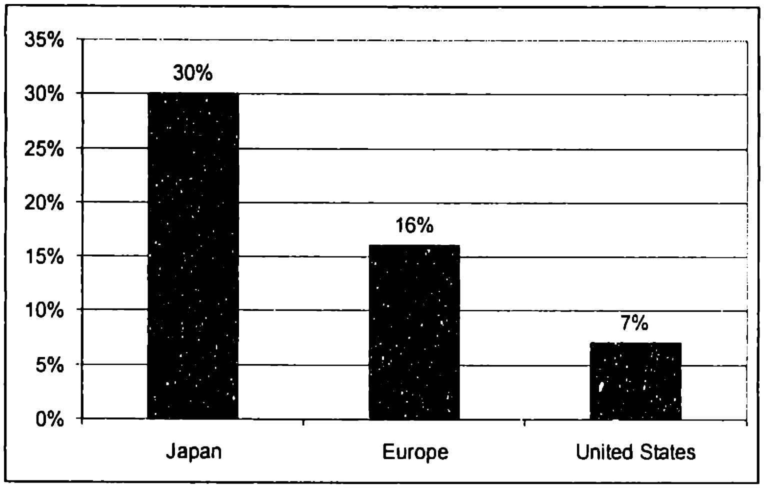


Figure 8-2: Supplier's Share of Engineering Effort [Clark, Fujimoto, 1991]

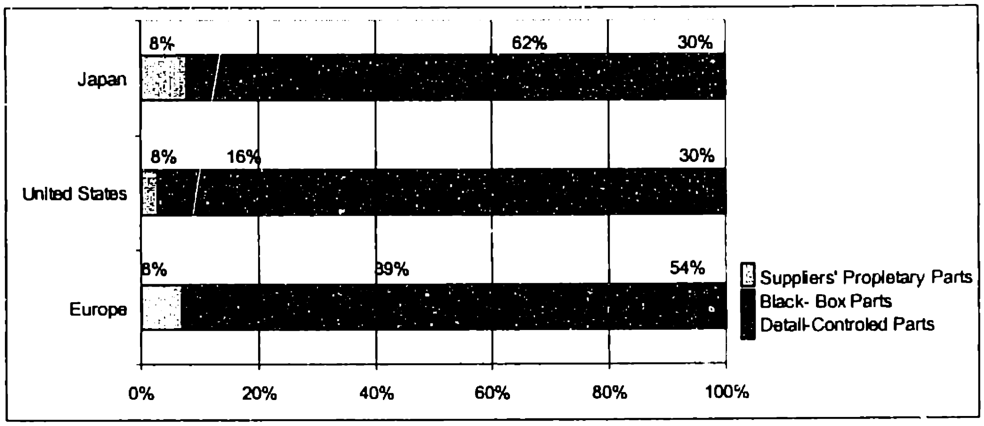


Figure 8-3: Types of Parts Produced by Suppliers [Clark, Fujimoto, 1991]

8.1.1 'Macro' level Methodology

There are some differences when designing an assembly system or fabrication system. At the same time, there are some differences when designing a new system or when converting an existing one. At the macro level or at a level where the steps can be generalized, the methodology is the same; however, when decomposing each of the macro steps into detailed steps the methodology becomes different. The next figure shows the macro-level steps needed to convert a production system, concurrently done with the integration of supply chain and integrating product development.

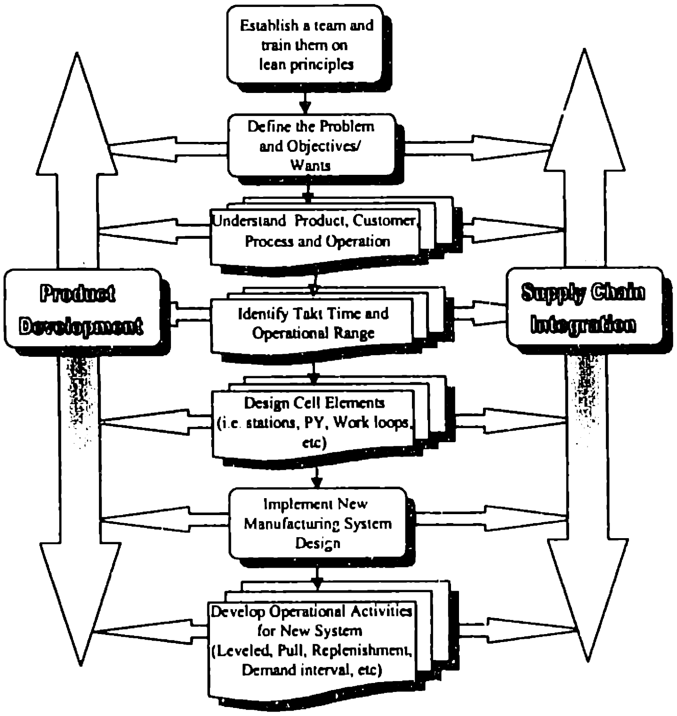


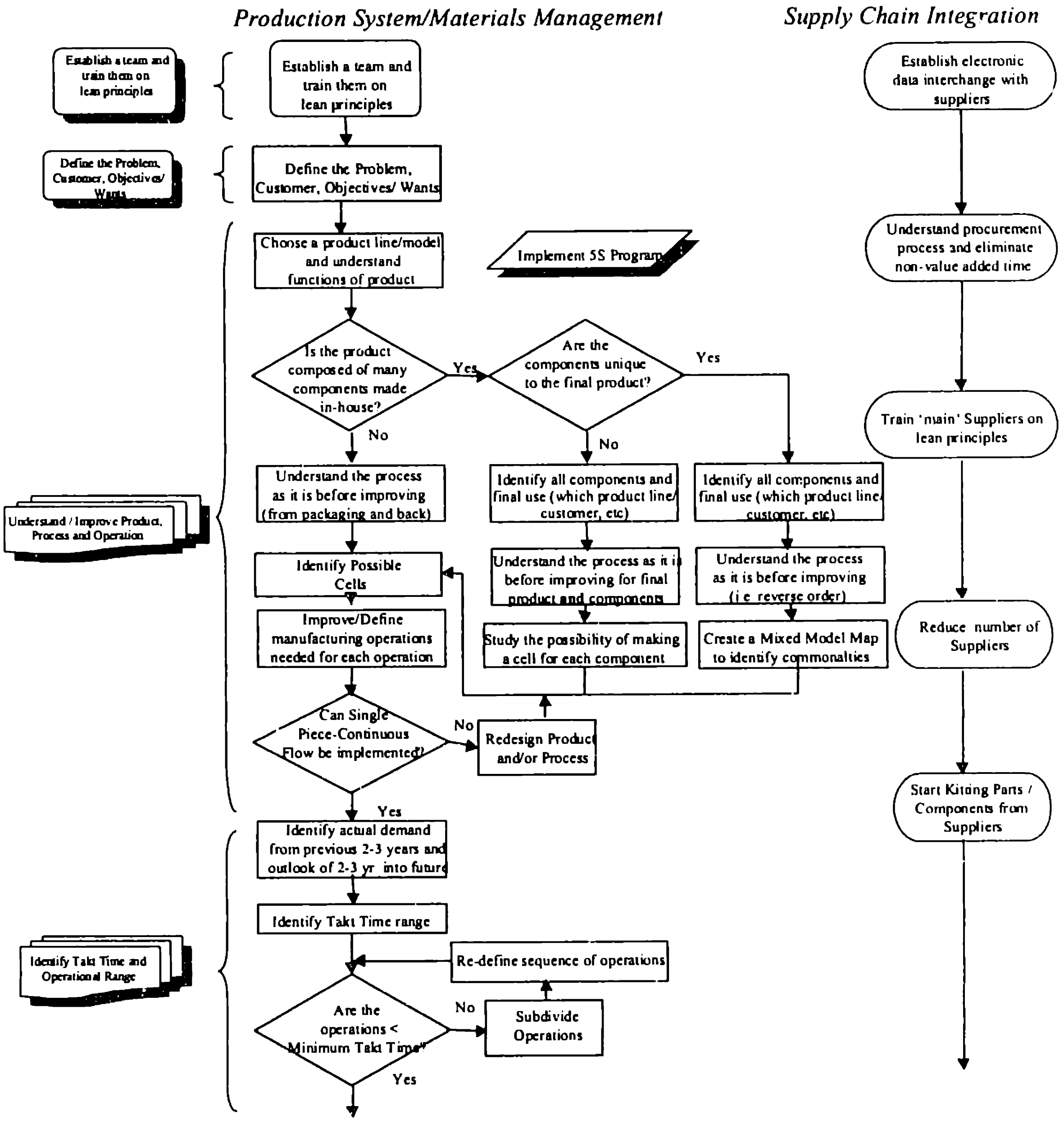
Figure 8-4: Implementation Steps of a Production System Design at a Macro-Level

8.2 Converting Existing Assembly System

The following flow chart presents a more detailed guideline for converting an existing assembly area (system) to a system that supports the design attributes of a lean production system. A *5-S Program* must be done concurrently with the steps mentioned in the next figure. The 5-S's stand for five Japanese words that constitute housekeeping. Today, practicing the five S's has become almost a must for any company engaged in manufacturing. The five steps of housekeeping are as follows:

- *Sort*: Distinguish between necessary and unnecessary items and discard the latter.
- *Straighten*: Put essential things in order so that they can be easily accessed
- *Scrub:* Clean everything – tools and workplace – removing stains, spots, and debris and eradicating sources of dirt.
- *Systematize:* Make cleaning and checking routine.
- *Standardize:* Standardize the previous steps to make the process one that never ends and can be improved upon

This steps are introduced very early in the process because it takes time, effort and discipline to keep up with the step involved in the *5-S's* Program.



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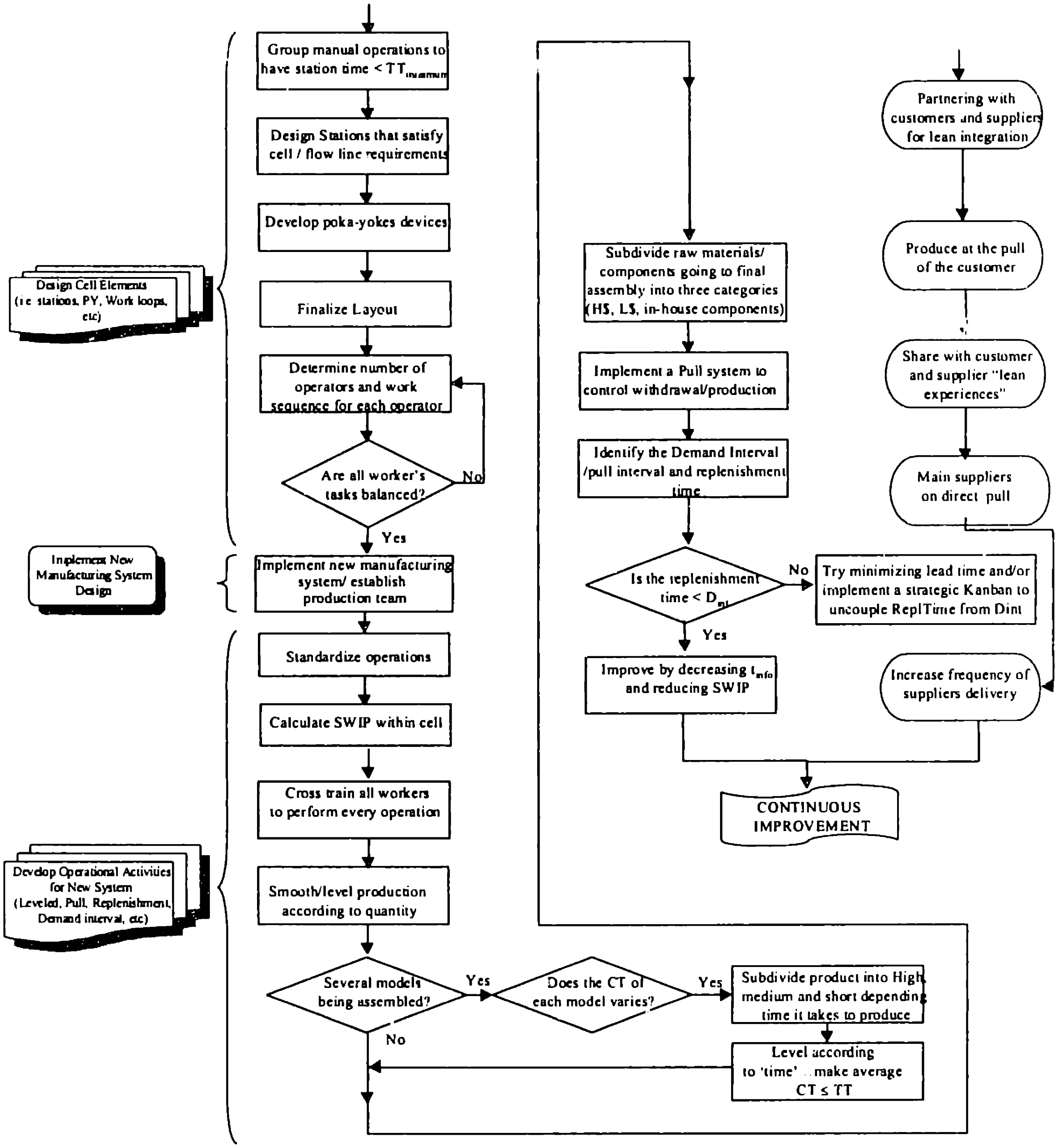


Figure 8-5 Converting existing assembly system (detailed steps)

8.2.1 Establish a team and train

The first step is always the most difficult, specifically in cases where the mentality of the people needs to be changed. A multifunctional team must be created before any improvement is done on the floor. The team should include engineers (design/manufacturing), production control, purchasing, sales/marketing, supervisors, workers and any other stakeholders of the process. Ideally, the team should be from 5-10 members and about half of the team should be workers including the supervisor of the area to be improved. It is important to pick people who have "high credibility". According to Schwartz (partner at TBM Consulting Group), the ideal team might include three to five production operators, a supervisor, a quality expert, a manufacturing engineer, two or three management people, and possibly a cost accountant or a salesman [Sheridan, 1997].

Training is the foundation for changing the mind set of the people directly and indirectly involved in the improvement process. In today's environment, transfer of knowledge is the core competence of any major company. The technology is always there or can be bought, but knowledge needs to be instilled in peoples' minds and that takes time and effort from both the instructor and pupil.

This training session must be extensive and should consist of case studies from other companies, physical simulations and any other activities that can increase the knowledge and understanding of the team. To create a lego simulation of these practices refer to Dobbs, 1998. It must be emphasized that top level management must support the team and the changes to be made.

8.2.2 Define the Problem and Objectives/Wants

The team needs to understand current problems they must solve. The team must work only on defining the problem and not on the solution. The team must set some goals as to where they want to be. If possible a definition of who the customers are (internal/external) must be done and explain how the problems are affecting the customers. Determine if the team goals are the same as the customer (internal/external) wants.

8.2.3 Choose a product line and understand functions of the product

The team must choose a product line/series they want to improve. A product line/series is the same as the product model and all of its different modifications (i.e. product/group family). For example, an aircraft engine company can have different engine series such as F500, T67, H34. Within those engine series, there could be different models, like F500-A1, F500-A2, etc. If the team is trying to improve the F500 engine series, they need to consider all different models within that series.

Every person involved in the improvement activity needs to understand the functions of the product and how those functions are achieved. This must be done to have a clear understanding of the product when analyzing the manufacturing system to be improved.

8.2.4 Is the product composed of many components made in-house?

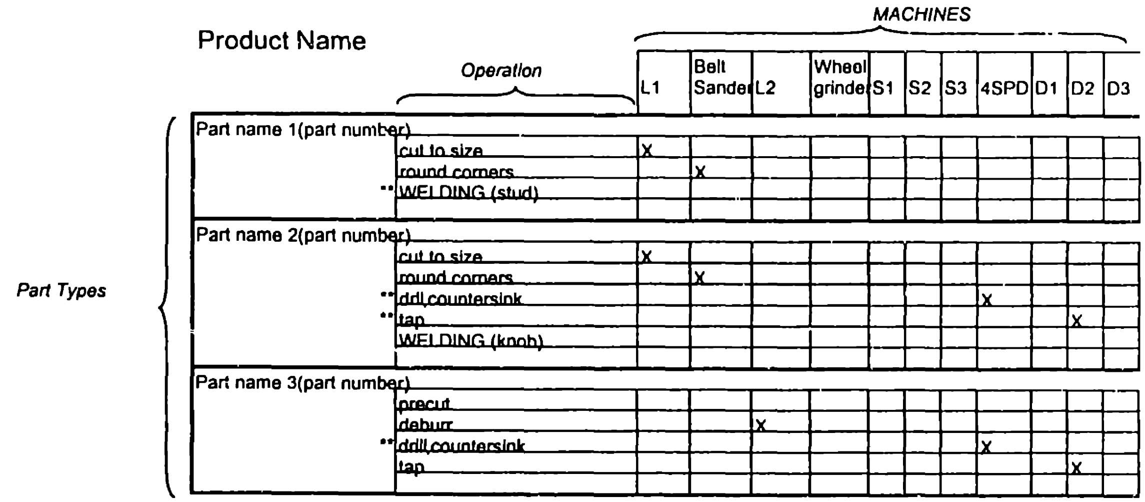
The reason for this question is twofold. First, to make the improvement process easier and secondly, to start thinking about different possibilities of layout.

a) If no, then go to next step
b) If yes, then: *Are the components unique to the final product?*
    1) If yes to *b)*, then:
        I) Identify all components
        II) Understand process as it is (*look at next step for explanation*)
        III) Create a mix-model-process map to identify process commonalties.
    2) If no to *b)*, then:
        I) Identify all components and final use (to which product are they going?)
        II) Understand process as it is for the final product and separately for each component (*look at next step for explanation*)
        III) Study the possibility of making a cell for each component

TOOLS

Mix-Model-Process Map:

- Equipment/machine go horizontally on the top portion
- Parts/Products go vertically
- Operations or process is defined next to each part name.



MACHINES

Product Name

Part Types

	Operation	L1	Belt Sande	L2	Wheel grinde	S1	S2	S3	4SPD	D1	D2	D3
Part name 1(part number)												
	cut to size	X										
	round corners		X									
	** WELDING (stud)											
Part name 2(part number)												
	cut to size	X										
	round corners		X									
	** ddl,countersink								X			
	** tap										X	
	WELDING (knob)											
Part name 3(part number)												
	precut											
	deburr			X								
	** ddl,countersink								X			
	tap										X	

Figure 8-6: Mixed-Model-Process Map to design a flow line or cell by grouping process or machines common to a product family

8.2.5 Understand the process as it is before improving it

Begin with packaging or shipping, taking the product out of the box and start defining the different steps and asking always "4 Whys and the 1 How" [Shingo, 1986]. This means to clearly understand what, when, where and why each operation is made and how it is done. During this step, the mind-set should be to look at the current operations but also identify those that are not adding any value and eliminate them. Do not try to solve the problem yet. Write down ideas and recommendations but do not change anything.

TOOL a)

To make the process visual and for the understanding of everybody, instantaneous (Polaroid) pictures could be taken at each step, then post the steps in a wall and once the entire process is on the wall, the team could start eliminating non-value added operations. Identify current processing time for each operation.

TOOL b)

Another tool will be to develop a process map of all operations (figure 8-6). The process map in figure 8-6 consists of a macro view of all operations and then the process is broke down into furhter individual operations.

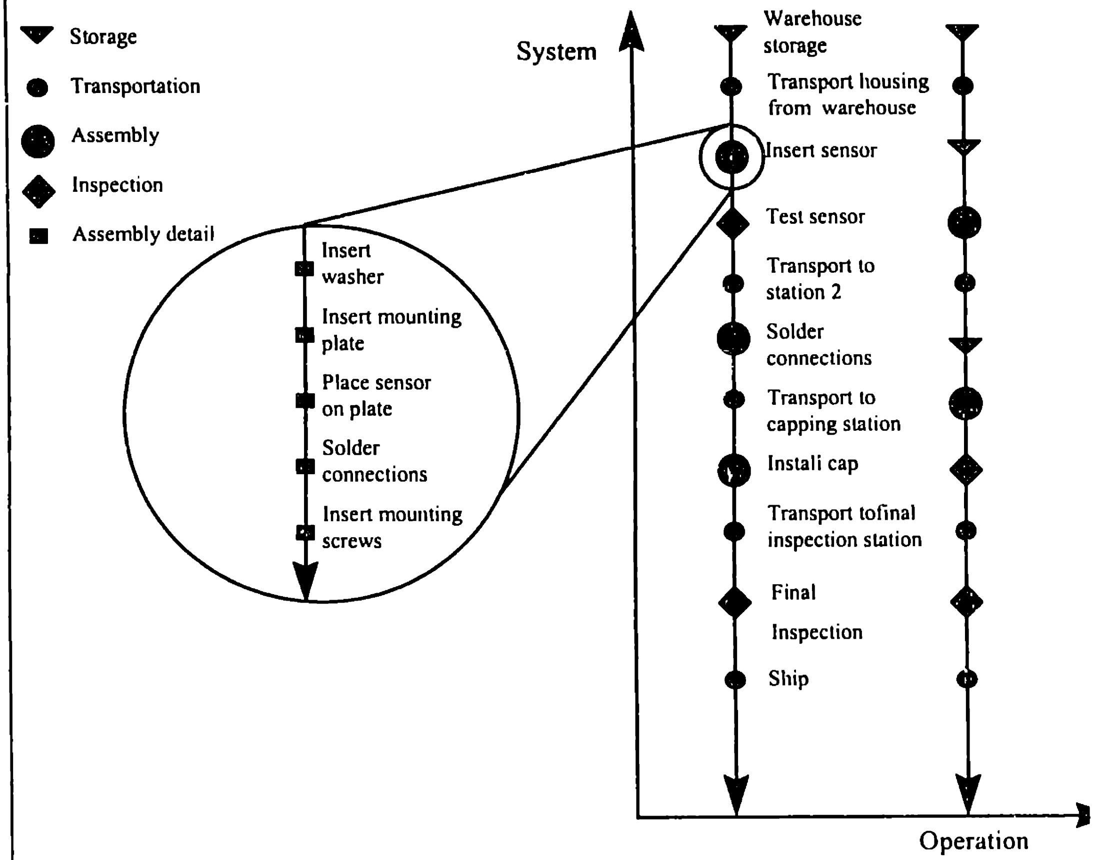


Figure 8-7: Process map of an assembly process

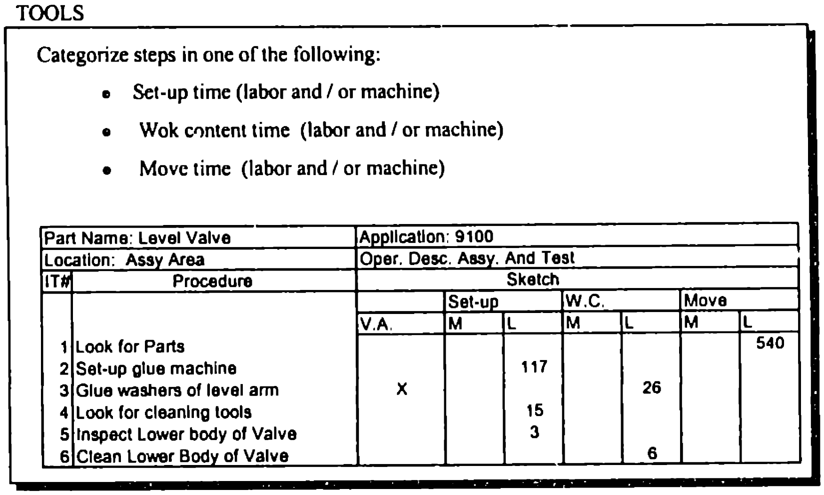
8.2.6 Identify possible cells

In this step, the team is not expected to come up with the final solution. The idea is to make some rough estimates of the cells that could be implemented depending on the data that was obtained during the previous steps. During the next steps, the efficiency and productivity of the different possible cells will be verified.

8.2.7 Improve/Define manufacturing process needed for each operation

The team should go back to the process map done during 8.2.5 and eliminate the non-value adding operations. A manufacturing process should be identified for each operation. For example, if shimming needs to be done in final assembly, should you use a piece of metal or use liquid epoxy? Or if a hole needs to be made, should you use a drilling machine or a punch press?

Every operation must be chosen to satisfy the system requirements. When each manufacturing operation is improved and when choosing a manufacturing process to perform the operation, the team needs to ask themselves if that operation is really needed and if so, how can they improve it to satisfy and improve the performance of the system and not the operation itself.



TOOLS

Categorize steps in one of the following:

- Set-up time (labor and / or machine)
- Wok content time (labor and / or machine)
- Move time (labor and / or machine)

Part Name: Level Valve		Application: 9100						
Location: Assy Area		Oper. Desc. Assy. And Test						
IT#	Procedure	Sketch						
			Set-up		W.C.		Move	
		V.A.	M	L	M	L	M	L
1	Look for Parts							540
2	Set-up glue machine			117				
3	Glue washers of level arm	X				26		
4	Look for cleaning tools			15				
5	Inspect Lower body of Valve			3				
6	Clean Lower Body of Valve					6		

Figure 8-8: Identifying non-value added operations and operation sequence

8.2.8 Can single piece-continuous flow be implemented

In the Chapter 5 (*Replenishment time < demand interval*) it was shown how using single piece-continuous flow is faster and more responsive than batch production and enhances defect traceability. During this step, the team needs to ensure that every operation can be performed in single piece flow. If the operation can not be done in single piece flow, a new process could be used (i.e. induction tempering instead of draw furnace from Chapter 4) or the product could be redesigned if it is not costly and if changes of customer requirements are not changed.

8.2.9 Identify Takt Time Range

This step is done to ensure that the manufacturing system to be designed is able to produce the maximum output to meet the customer demand on a daily basis. The idea is to create a manufacturing system that can work well in many different operating conditions.

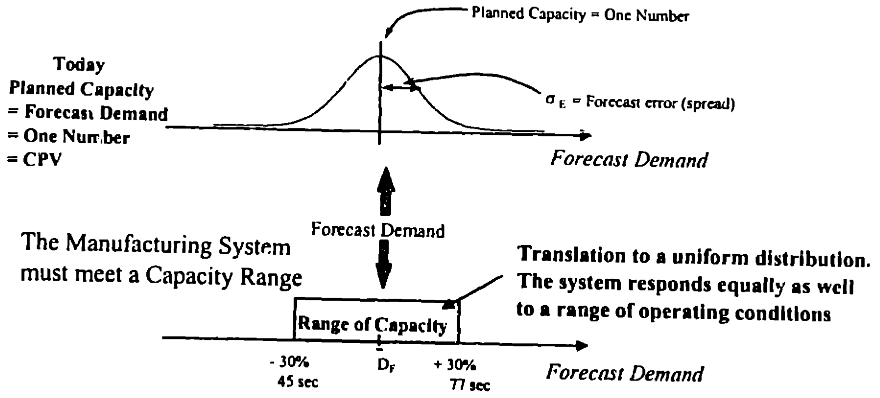


Figure 8-9: Design Manufacturing System for maximum demand cycle time and range of takt times (reprinted from Chapter 4, Figure 4-7)

First, the team should identify actual demand from previous two-three years and outlook of 2-3 years into the future. Take the highest demand and add X% to create the operational range. With the highest demand calculate minimum takt time, which is ,

$$\text{TAKT TIME}_{\text{minimum}} = \frac{\text{AVAILABLE TIME}}{\text{AVERAGE DAILY DEMAND}_{\text{with X\%}}} * (1-\alpha)$$

Where α is the allowance of the system, (85% as a goal for $1-\alpha$) and X is 20-30%. Available time is usually 7.3 hours per shift for one or two-shift operations and 7.08 hours per shift for three-shift operations; however, this number varies from plant to plant and it depends on the workforce and policies in the company. For example, an aircraft engine company visited was using 6.8 hours as the available time, while an automotive plant was using 7.3 hours.

This step must be done for the individual components and final product. If the components of the product are common among several product lines, the demand for each product must be consider in the takt time calculation.

8.2.10 Are the operations less than Minimum Takt Time

If the operations are less than minimum takt time, which was calculated in the previous step, then go to the next step, if not then operations need to be subdivided in such a manner that the minimum takt time is met. Before subdividing operations, the team must analyze the operations in more detail and study the possibility of improving the operations.

Figure 8-10 shows how Plant L (reprinted from Chapter 3) subdivided operations in the assembly cell to have an operational cycle time of each station less than the minimum takt time. Examples of how some companies have subdivided the operations are presented in Chapter 4

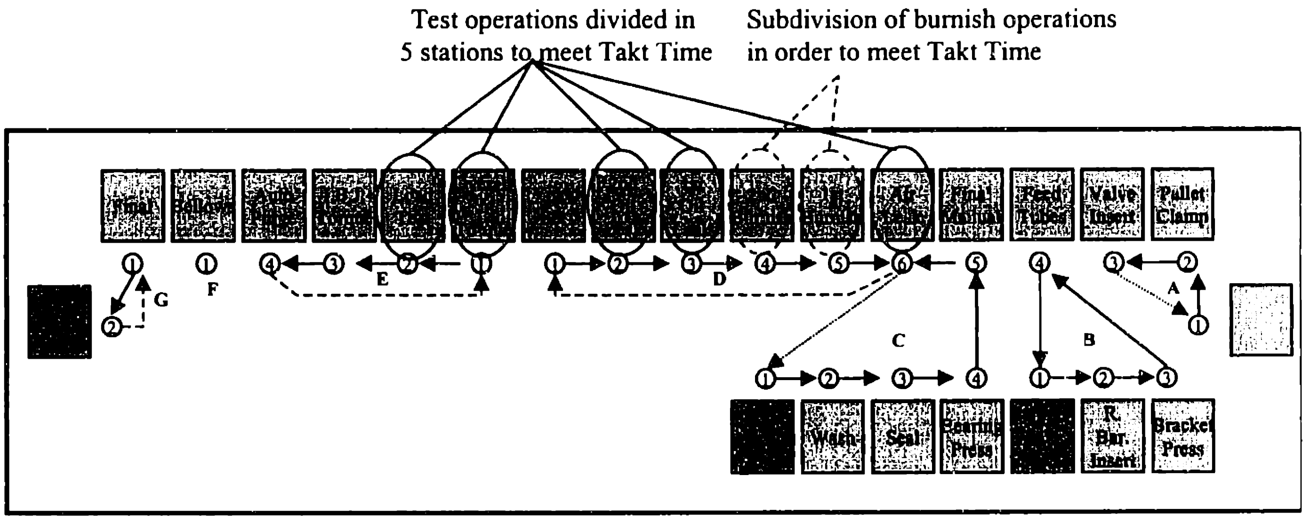


Figure 8-10: Subdividing operations in assembly at Plant L (reprinted from chapter 4)

8.2.11 Group manual operations to have station time < Takt Time

Once all the operations are less than the takt time, and have determined the sequence of operations, we can start combining some operations into stations. The station cycle time should be less than the minimum takt time as well. For example, if there are three manual operations, with times of 15, 25, 60 seconds respectively, and a takt time of 75 seconds, we could combine operations 1 and 2 into one station and leave operation 3 in another stations. For purely manual operations, the number of stations can be obtained using the following formula:

$$\text{Number of Stations} = \frac{\text{Manual Time to Assemble}}{\text{Takt Time}_{\text{minimum}}} \qquad (8.1)$$

8.2.12 Design station to satisfy cell/flow line requirements

Once all the operations are grouped together into stations, the next step is to design the stations that would satisfy the following requirements:

- Material fed from the back of the stations or from some position that does not disrupt production.
- Tools required for the operations conveniently located for the operator. If possible spring-loaded cable returns, so that the operator can simply let go of the tool when done with it.
- Height adjustable station (if possible).
- Stations on wheels for easy relocation.
- Operations posted on the stations.
- Place materials and tools in a given area and in the same sequence as the work.
- Integral Frame
- Flexible utility drops
- Simple Leveling System
- General simplicity designed into the entire station. Make it inexpensive and simple, so that the work team is not afraid of making changes.

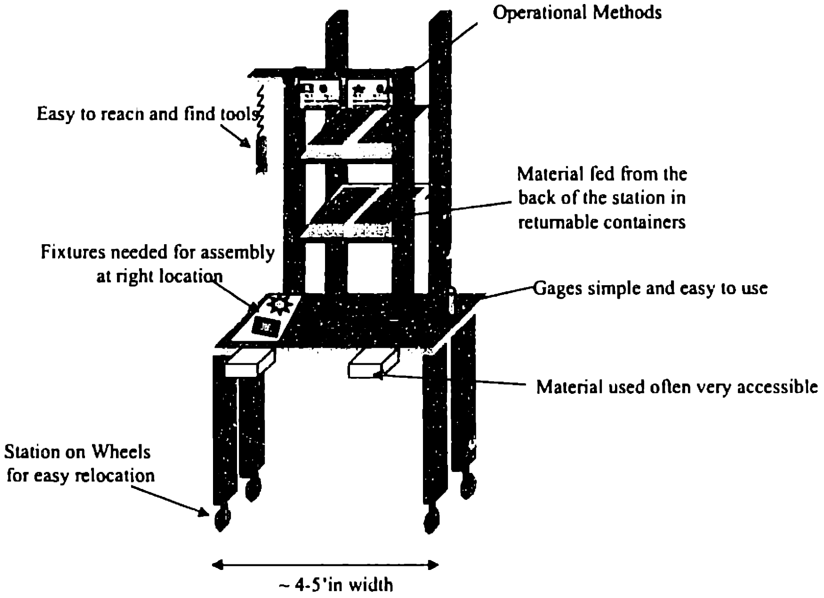


Figure 8-11: Station requirements for cell/flow line

8.2.13 Develop poka-yoke devices

Poka-yoke devices should be added to prevent defects from happening and detect those defects that occur. The following guidelines help in the design of a poka-yoke for assembly:

- Collect data of past defects
- Determine the priority of each defect based on :
  - cost of the defect (hours spent on rework, is it a customer return, etc)
  - occurrence (how often it happens)
- Determine location of Poka-yoke (PY)
  - If part is assembled and not touched by a tool (i.e. wrench), then place the electric eye on the container of the part to detect operator removing the part (PY1)
  - If part is assembled and touched by a tool, then do not place an electric eye built place the Poka-yoke on the tool (PY2a and PY2b)
    a).PY on the tool if the operator is applying some engineering specification to the product with the tool (e.g. torque sensor on wrench).
    b).PY the presence of the tool if operator is using the tool to install some part but not introducing any engineering specification (e.g. electric eyes to detect operator remove the tool)
  - Confirm operations with sounds to minimize eyeball movement by installing a beeper that beeps every time an operation has been checked.

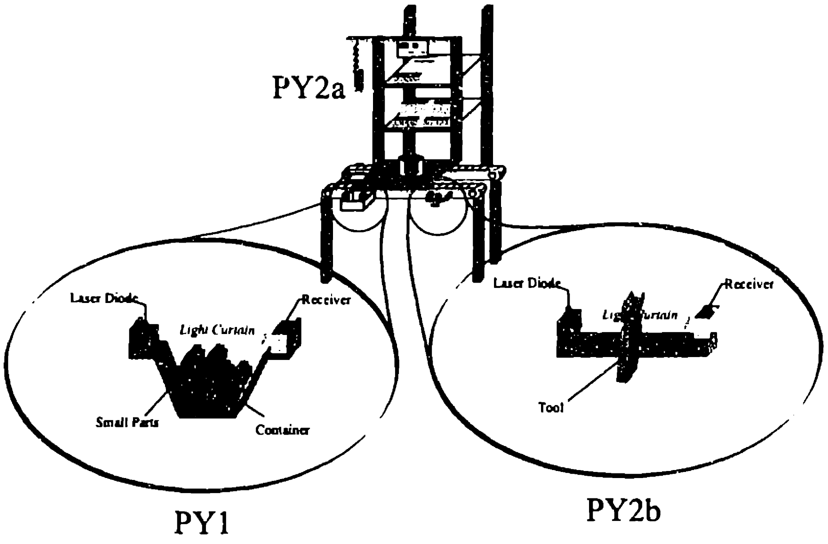


Figure 8-12: Poka-yokes in assembly

8.2.14 Finalize Layout

The team must decide and finalize the layout of the assembly area. The layout is dependent on the type of product being assembled. There are several options below,

- If product is small and not heavy for the operator to carry it from station to station
    - U-shaped cell or two parallel rows

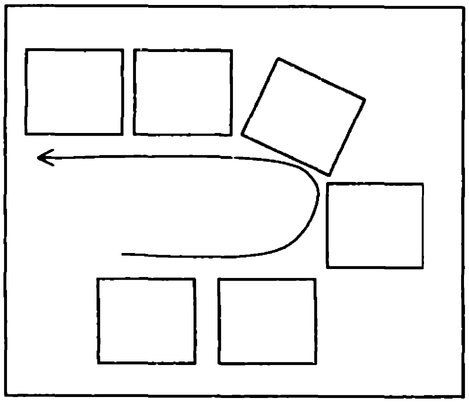


Figure 13a: "U" Shaped Cell

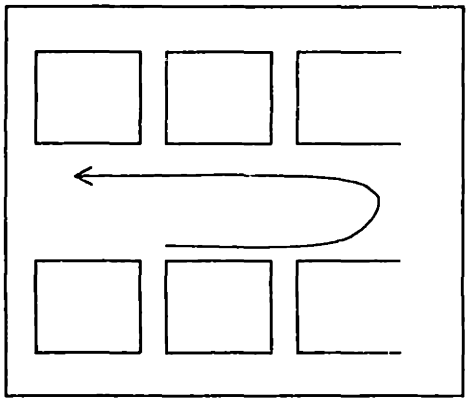


Figure 13b: Parallel rows

- If product is large and heavy for operator to carry, then need more open space to move the product from station to station in a cart or dolly
    - Fish-bone layout

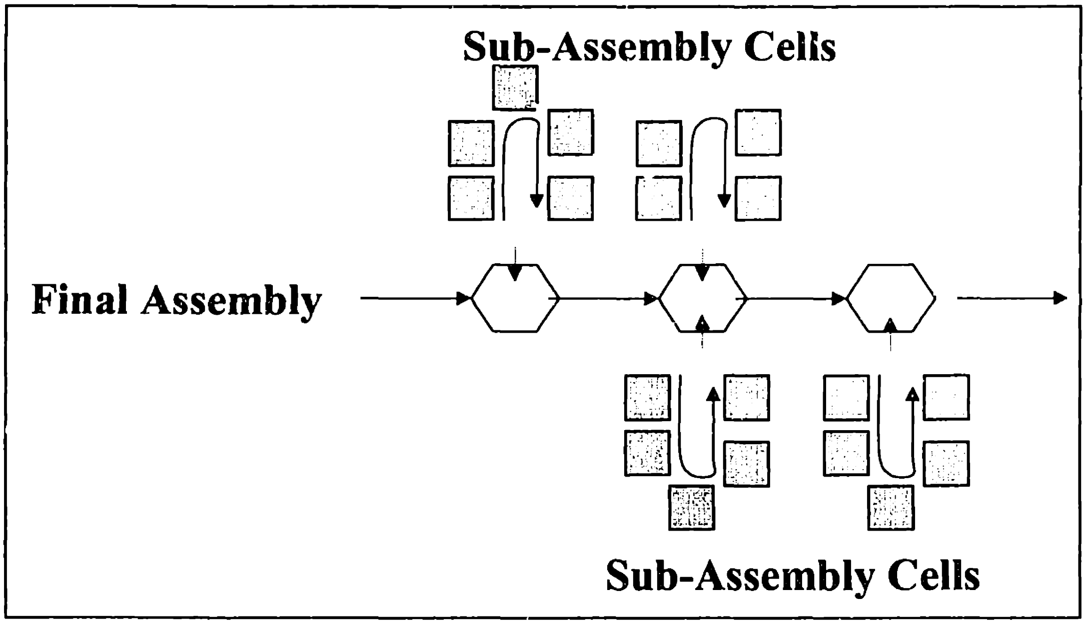


Figure 8-14: "Fish-Bone" Layout

- For a cell with two part types, which each require one machine that the other part type does not use, the best layout (if processing sequence allows it) is given in Figure 8-15 [Colosky, 1997].

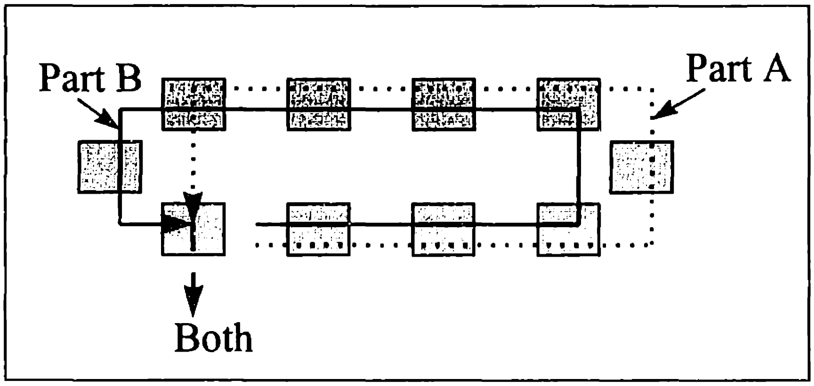


Figure 8-15

- For cells where there are several part types, all of which share a few machines, but some of which require additional machines, the layout should be (if processing sequence allows it) as in Figure 8-15, where the order A-B-C represents the ranking in terms of volume of parts produced in a given time period.

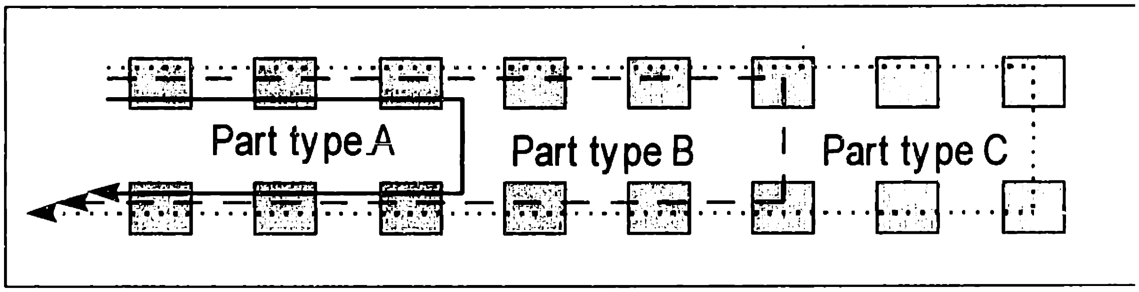


Figure 8-16

Some general characteristics for a cell or flow line are as follows,

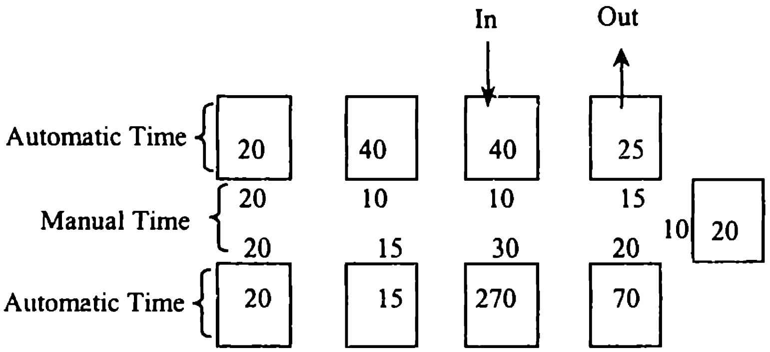
- Not a single process stage. Multiple processes per cell.
- For manual conveyance, start with U-cell
- If auto conveyance is necessary (heavy parts, >10 lbs), start with small, in-line power-free conveyor. The conveyor can be interfaced with the PLCs and Poka-yokes in the line so that the part does not move unless all poka-yokes have been triggered
- Machines/stations placed close together around manpower (operators inside the cell)
- Cycle time to allow for visual inspection
- Inspection built into the process
- Make use of visual control devices: electronic counter display to indicate actual versus planned production by hour for the cell

8.2.15 Determine number of operators and work sequence for each operator

$$\text{Number of Operators} = \frac{\text{Manual Work Time} + \text{Walking Time}}{\text{Takt Time}}$$

The manual work time includes any time needed for load/unload and any other manual time needed to perform the operations. If the number of operators is not an integer number, then either improve the operations so that the number is an integer or the number is rounded to the next integer number.

Example:



Walk Time of 3 sec between machines

Figure 8-17: Cell layout

$$\sum \frac{\text{Manual Time + Walking Time}}{\text{Min. Takt Time}} = \frac{197 \text{ seconds}}{100 \text{ seconds/part}} = 1.97 \text{ operators} \longrightarrow \text{round to 2 operators.}$$

Verify:

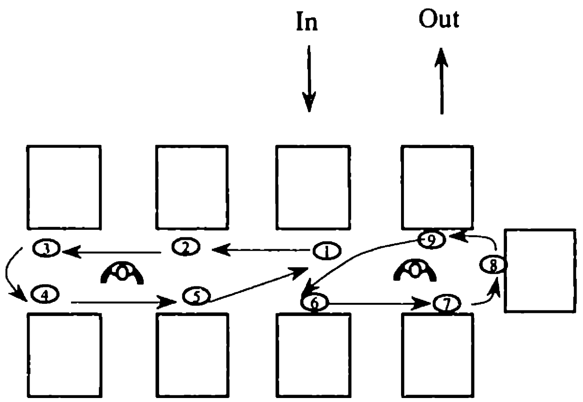
$\sum$ Manual Time of Operation 1-5 = 90 min

$\sum$ Manual Time of Operation 1-6 = 123 min *Exceeds Takt Time of 100 seconds!!*

Therefore, one operator for Operations 1-5

$\sum$ Manual Time of Operation 6-9 = 75 min

Therefore, another operator for Operations 6-9



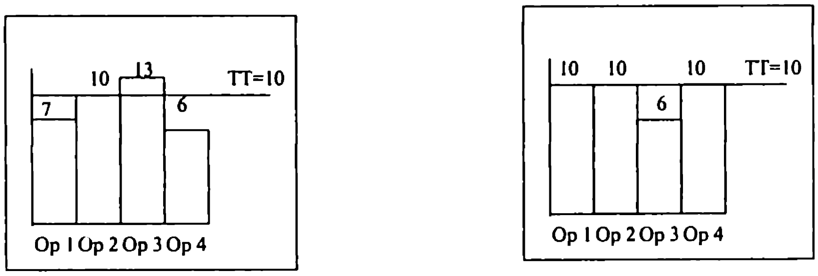
Step #	Walk	Manual	Auto	Operators
1	3	10	40	▲
2	3	10	40	
3	3	20	20	
4	3	20	0	
5	3	15	15	▼
6	3	30	270	▲
7	3	20	70	
8	3	10	20	
9	3	15	25	▼

Figure 8-18: Final Cell Layout with number of operates and work sequence for each operator

Once the number of operators is determined, the sequence of operations can be determined from the layout and table above. The number of operators and the time for each operation will be verified during step number 8.2.18 when the standard work combination routine sheet is developed.

8.2.16 Are all 'work loops'/ worker tasks balanced?

A work-loop is composed of a number of operations performed by a worker every cycle which is less than the takt time. The worker tasks are the operations that make up a work loop. When determining how well the system is balanced, both work-loop and worker tasks, need to be analyzed. The next figure presents two possible scenarios. Each bar can be either a work-loop or a work-task. The figure on the left represents a non-balanced work-loop or work-task, while the figure on the right represents the improved system with balanced work loops and tasks. It can be seen that for the same throughput time, one cell can produce at a faster cycle time than the other just by balancing the operations in the line correctly. When the loops or work tasks are not balanced, the layout may need some modifications.



The best the cell can produce is one unit every 13 minutes

A unit comes off the cell every 10 minutes to meet the customer demand

Figure 8-19: Balancing Operations

8.2.17 Implement changes/establish production team

Once the team knows the layout of the cell and has performed previous steps, the team is ready to implement the changes on the manufacturing floor. There must be full cooperation from people on the floor, maintenance and any other group that is in charge of moving the equipment. This movement must be done as soon as possible to start production once again. If the relocation of equipment takes more than two days, production must be done ahead or in another line. For each product line an interdisciplinary production team must be selected and located next to the line if possible. This team must be composed of all the indirect personnel (engineers, planner, purchasing, etc) in charge of supporting the line.

A team and team leader should be chosen to work on the line. Each team, about eight employees working under a team leader, has the responsibility and authority to design their own jobs [TMC, 1992]. Working together, the team discovers new ways to smooth the flow of production, to raise quality, and to improve their own conditions.

The team leader is in charge of maintaining the line running. This means that the team leader needs to make sure there is enough material available, perform preventive maintenance, replace an absent worker, repair any defective parts or non-conforming material, prepare standard operations and train the operators in the cell. In other words, the team leader should be consider a multi-tasking supervisor.

8.2.18 Standardize operations

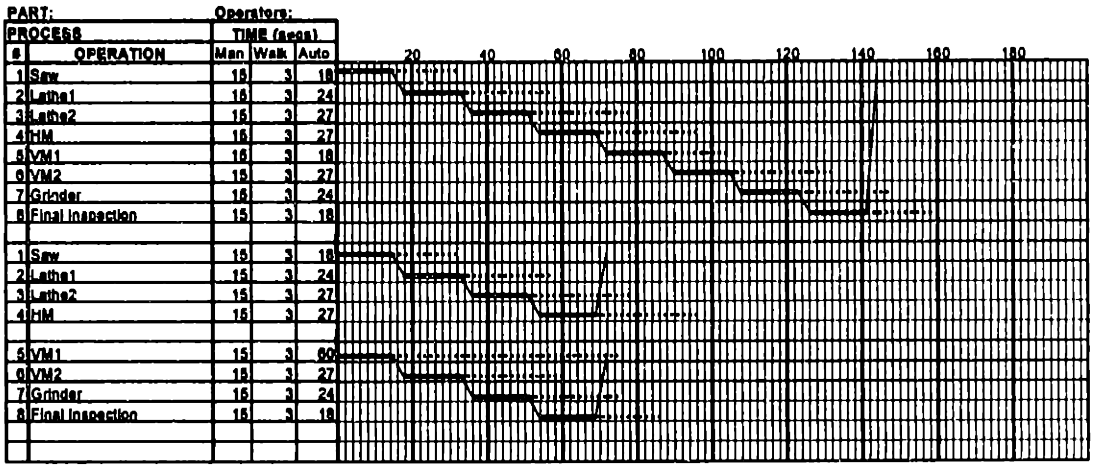
Once the line is running, the team leader should create and maintain the standard operation routine sheet (Figure 8-20a) or operational method sheet (Figure 8-20b). It is important to revise the standard operations regularly, since they are always imperfect and operations improvement are always required in a process. The standard operations sheet can be used for visual control in three major areas:

- Guideline for each worker to keep his standard operations

- Helps supervisor or team leader verify each operator is following standard operations
- It allows the senior manager to evaluate the supervisor's ability, since the standard operations must be revised frequently by improving operations of the process [Monden, 1993]

Appendix A explains how to fill out a standard work operation routine sheet.

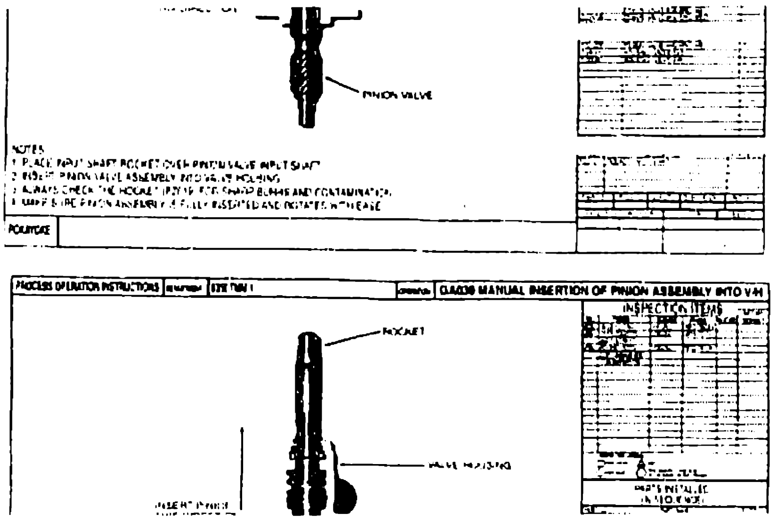
TOOLS



PART:
Operators:

PROCESS		TIME (secs)		
#	OPERATION	Man	Walk	Auto
1	Saw	15	3	18
2	Lathe1	15	3	24
3	Lathe2	15	3	27
4	HM	15	3	27
5	VM1	15	3	18
6	VM2	15	3	27
7	Grinder	15	3	24
8	Final Inspection	15	3	18
1	Saw	15	3	18
2	Lathe1	15	3	24
3	Lathe2	15	3	27
4	HM	15	3	27
5	VM1	15	3	60
6	VM2	15	3	27
7	Grinder	15	3	24
8	Final Inspection	15	3	18

Figure 8-20a: Standard Work Routine Sheet



NOTES
1. PLACE INPUT SHAFT POCKET OVER PINION VALVE INPUT SHAFT
2. INSERT PINION VALVE ASSEMBLY INTO VALVE HOUSING
3. ALWAYS CHECK THE POCKET [illegible] FOR SHARP BURRS AND CONTAMINATION
4. MAKE SURE PINION ASSEMBLY IS FULLY INSERTED AND ROTATES WITH EASE

PROCESS OPERATOR INSTRUCTIONS
MANUAL INSERTION OF PINION ASSEMBLY INTO V-H

Figure 8-20b: Operations Method Sheet

8.2.19 Calculate standard-work-in-process within the cell

The work in process within the cell is dependent on the manual time and the automatic time of the machines or equipment. The standard work-in-process (SWIP) within the cell can be obtained with the following formula (equation 5.3 reprinted from Chapter 5)

$$\#\text{ of SWIP}_{\text{within cell}} = \frac{\text{Automatic time + load/unload time}}{\text{Takt Time}}$$

In other words, one SWIP is placed when the sum of time (auto + load/unload) is equal to the takt time. When automatic time, load and unload time exceeds takt time and operation time can not be subdivided or when an out of area operation exceeds takt time a buffer is added to establish a decoupling effect.

The next figure (figure 8-21) shows an example on how to calculate SWIP within the cell. Assume the Takt Time for the cell is 100 seconds and the manual and automatic time are in the table in figure 8-21.

$\sum$ Manual Time + Auto Time 1-2 = 100 sec $\longrightarrow$ one SWIP

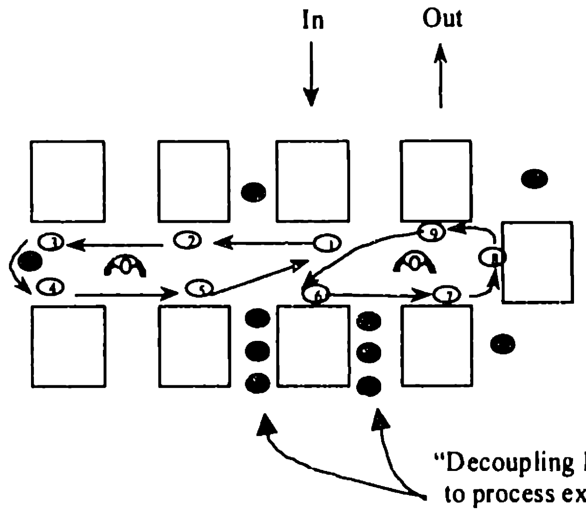
$\sum$ Manual Time of Operation 3-5 = 90 sec $\longrightarrow$ one SWIP

$\sum$ Manual Time of Operation 6 = 300 sec $\longrightarrow$ three SWIPs

Since the time is >> Takt time, to create the 'curtain effect',
Three more SWIPs are waiting before or after collectively.

$\sum$ Manual Time of Operation 7 = 90 sec $\longrightarrow$ one SWIP

$\sum$ Manual Time of Operation 8-9 = 70 sec $\longrightarrow$ one SWIP



Step #	Walk	Manual	Auto	SWIP ●
1	3	10	40	
2	3	10	40	●
3	3	20	20	
4	3	20	0	
5	3	15	15	●
6	3	30	270	●●●
7	3	20	70	●
8	3	10	20	
9	3	15	25	○

Units for Manual, Auto and Walk are in seconds

● = 1 SWIP

Figure 8-21: Calculating the number of SWIP within a cell

Most of the time in pure manual assemblies, the station time or operator's manual time at a station is very close to the takt time (operational time must be < takt time); therefore, the number of $SWIP_{within\ cell}$ in equation 5.3 equates to 1. For example, in the final assembly of an aircraft engine, there would be a kanban square or SWIP of 1 between each of the major stations since the manual time at a station is very close to the takt time (figure 8-22). The kanban square ensures an available component all the time and assures production only when it is needed, which is when the kanban square is empty or pulled from the subsequent station.

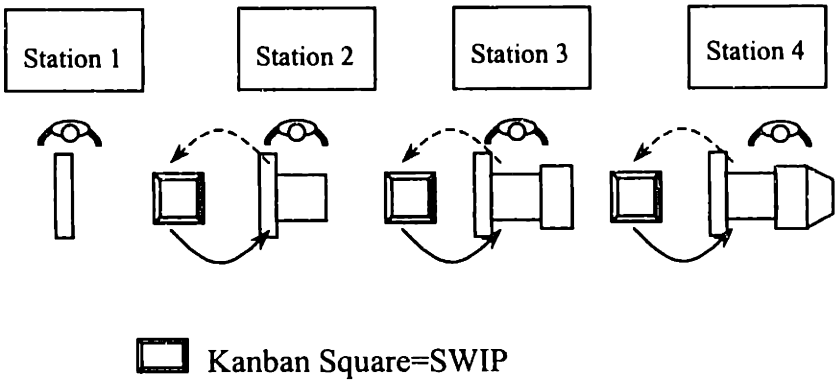


Figure 8-22: Example of SWIP Calculation in Aircraft Engine Assembly

8.2.20 Cross train workers to perform all operations

Operators must be cross-trained on all types of equipment and processes within a newly created cell thereby minimizing disruption and variability to production due to absenteeism, vacation, etc. This activity must be done continuously.

TOOL

Table 8-1 is a good visual tool to keep track of how well the operators are trained on the floor. This tool is also good to implement a salary scheme. Some companies pay operators based on the knowledge. The more full circles an operator has, the more money they get. The circles could also be for different tasks, i.e. one area has four distinct job tasks

	PRODUCT or OPERATION		
OPERATOR NAME	1	2	3
Operator 1	◔	⊕	◕
Operator 2	◑	◑	⊕
Operator 3	◑	⊕	⊕
Operator 4	●	⊕	◔

◔	25% of operations known
◑	50% of operations known
◕	75% of operations known
●	100% of operations known

Table 8-1

8.2.21 Smooth/level production according to quantity

For detailed information on smoothing production according to time, refer to Chapter 5 on Level Production. Briefly, leveling quantity production takes the monthly amount (or 2-4 months) of demand and divided equally into daily or weekly quantities depending on the production rate (i.e. aircraft engines is weekly, while automotive components is daily).

Leveling according to quantity would be enough for a production line that is either assembling different models with no variation in production time from one model to another or assembling only one model in the line. If the line assembles several models that vary in production time then continue with the next step.

8.2.22 Mixed Model Production (leveling production time)

In this case, the production needs to be leveled according to quantity and assembly time, so the average cycle time to produce the different models is less than or equal to the takt time (figure 8-23 reprinted from chapter 5). Refer to Chapter 5 for a more detailed explanation on leveling according to time.

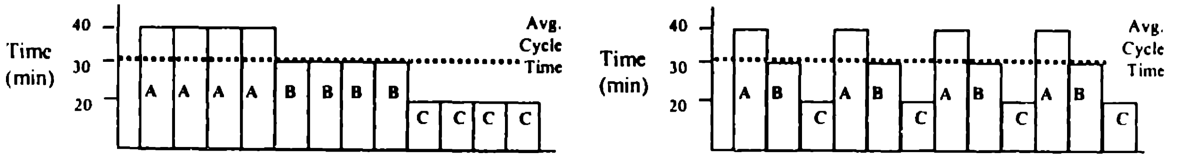


Figure 8-23 a) sequence that causes line stoppage; b) sequence that enables avrage cycle time < takt time

Usually the easiest manner to level according to time, is to categorize the different models into high, medium and low depending on the man-hours it takes to produce the models. Once this subdivision is made, the production could be scheduled in the sequence of high, medium, and small in order to produce at an average cycle time less than the takt time.

8.2.23 Subdivide material/components going to final assembly into three categories

The subdivisions are made to minimize inventory, easier material management and minimize cost. The three categories are:

> *High value materials*: The Pareto rule applies in this case most of the time. Usually, 20% of the part number count for 80% of the product cost(Figure 8-24). This type of material should be placed in direct pull from the supplier. At the beginning, this material can come from the controlled storage area inside the producing plant. Reduction of inventory should be emphasize to this type of material rather than the low cost items.

<u>Low value materials:</u> This material is usually nuts, bolts and material that is economically made in large lots. This material that is not consider to be expensive in the product cost, could be setup on a "bread-man" system, where every day or every week a person fills in empty or medium empty containers. The second option is to place a 'min-max' system based on the economic order quantity from the source and replenishment time.

<u>In-house components:</u> All the in-house components should be placed on a pull system. There are many different methods in which a kanban system can be implemented for in-house production. If material is small and not heavy a simple container is good for conveyance purpose. If the material is heavy and/or bulky, it can be placed on a cart and create kanban squares or marks on the floor. If there is no cart on the marked square, that triggers the production of another cart. The reason for implementing a pull or kanban system for the 'in-house' components is to autonomously control the production of the plant and minimize complexity involved with scheduling tools.

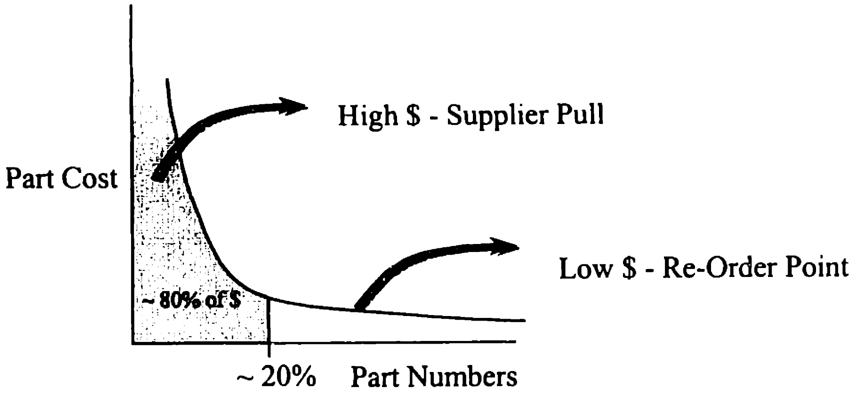


Figure 8-24: Subdivision of material into high and low value

A Kanban is a communication signal used to pull products and materials though the manufacturing process. A kanban can be any inexpensive device that would signal either production or withdrawal. Figure 8-25 shows some examples of kanban devices.

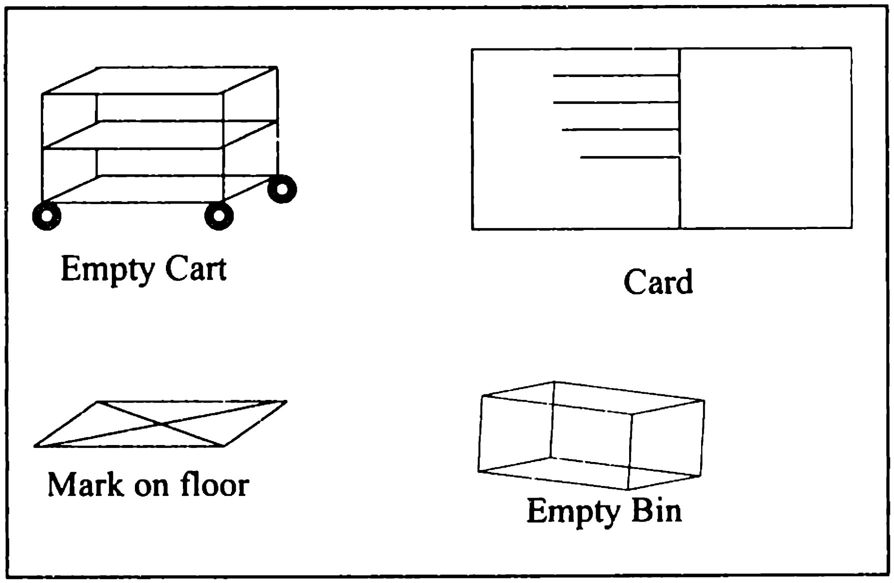


Figure 8-25: Example of possible kanban signals

There are two kinds of kanban:

Withdrawal Kanban: specifies the kind and quantity that subsequent process should withdrawal from preceding process

Production-Ordering Kanban: specifies the kind and quantity of product which the preceding process must produce

A simple formula used to calculate the number of production-ordering kanbans between cells (for components made 'in-house') is the following:

$$\text{\# of Kanbans} = \frac{\text{Average Daily Demand}*(\text{Lead Time})*(1+\text{safety stock})}{\text{Container Capacity}}$$

where lead time is the time it takes to replenish the part that is on the container, transportation time, queing time, etc. The safety stock coefficient must be less than 10% and should be eliminated once the system is running smoothly.

A withdrawal kanban is used for controlling the material (high and low value) not produced "in-house". Refer to chapter 5 for a more detailed explanation on how to calculate a withdrawal kanban.

8.2.24 Identify the demand interval/pull interval and replenishment time

Since most of the System's pieces are in place, now is the time to identify the demand interval or pull interval from the customer or how often the customer wants to pick up the product. If the company is in the make-to-order business, the demand interval should be based on a competitive time frame. That is, the company should set an aggressive demand interval based on customer orders and competition. The internal customer demand interval or pull interval should be established too. The pull interval is how often final assembly is picking up a container from a sub-assembly or from fabrication.

The time to replenish a container needs to be determined. In a cell or production line operating under single piece flow with the right amount of SWIP (previous step) and a cycle time less than the takt time, the replenishment time can be calculated using equation 5.2 from Chapter 5:

$$\text{Replenishment Time} = TT*(\#\text{ of stations})*1\text{ part} + (C-1)*TT \qquad (5.2)$$

where TT is the actual Takt Time and C is the container capacity

8.2.25 Is the replenishment time less than the demand interval?

a) if no, then: try minimizing the throughput time and/or implement strategic Kanbans to uncouple the replenishment time from demand interval
b) if yes, then: improve current state by decreasing t_{info} amount (increasing frequency) and reducing the standard work-in-process quantity

8.2.26 Continuous Improvement

Continuous improvement means to constantly evolve, modify and improve the system that has been implemented. Continuous improvement events are targeted to specific areas in the manufacturing floor. The continuous improvement activity does not need to be planned. For example, a team leader or operator proposes an idea on how to improve certain operation, and after some discussion with the team if it is appropriate, the changes must be done immediately. Operators are the key players in the continuous improvement since they are the 'end users' of the system implemented.

The improvement events should be focused not only in the process analysis, but also in cost analysis and value engineering. During cost analysis, the team must try to determine the real costs in the process and emphasize what can be improved through improvement events. Value engineering is important as well to analyze the product and achieve the necessary functions in the most profitable manner.

8.3 Designing New Assembly System

At the macro level , the steps for designing a new assembly system or converting an existing one are the same. However, there are some differences at the micro-level. Usually, when designing a new assembly system, the stations or equipment are not in existence; therefore, it is needed to predict operational time to design the required stations. Techniques developed by Boothroyd and Dewhurst could be used to estimate the assembly time by using pre-determined times depending on the operations performed. Those techniques are now incorporated into a software program developed by Boothroyd Dewhurst Inc that would calculate the assembly time for different operations.

The next figure shows the flow chart for designing new assembly systems. The major difference between the methodology for new assembly systems and existing assembly systems is the order of some steps and the calculation of operational time. Figure 8-26 shows the steps needed to design a new assembly system.

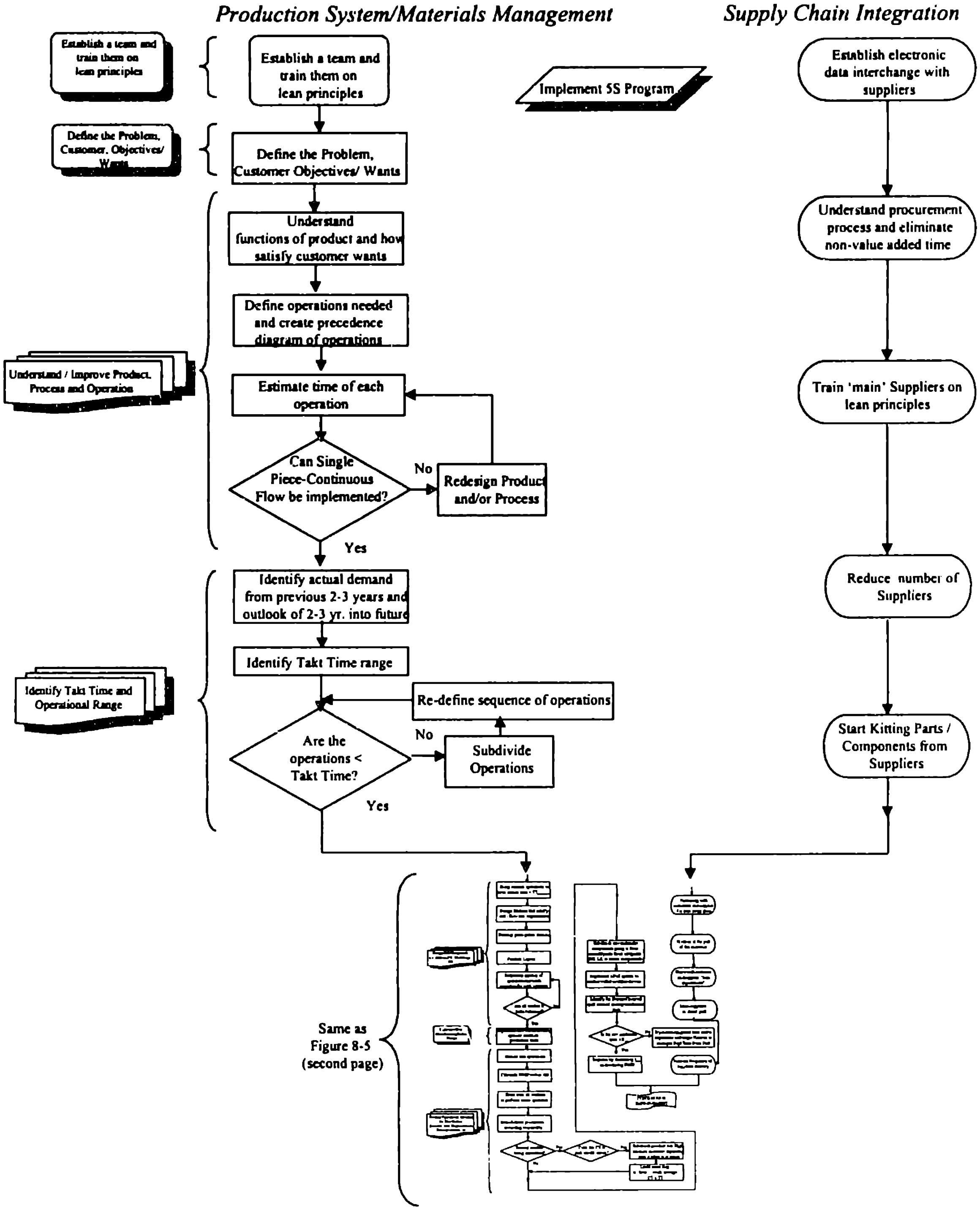


Figure 8-26: Designing New assembly system (detail methodology)

In instances where the operations have never been done before, the cycle time of each operation can be calculated using the technique developed by Boothroyd and Dewhurst (Figure 8-27)

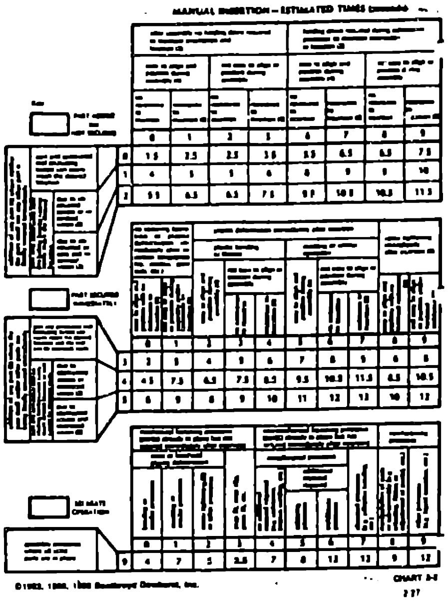
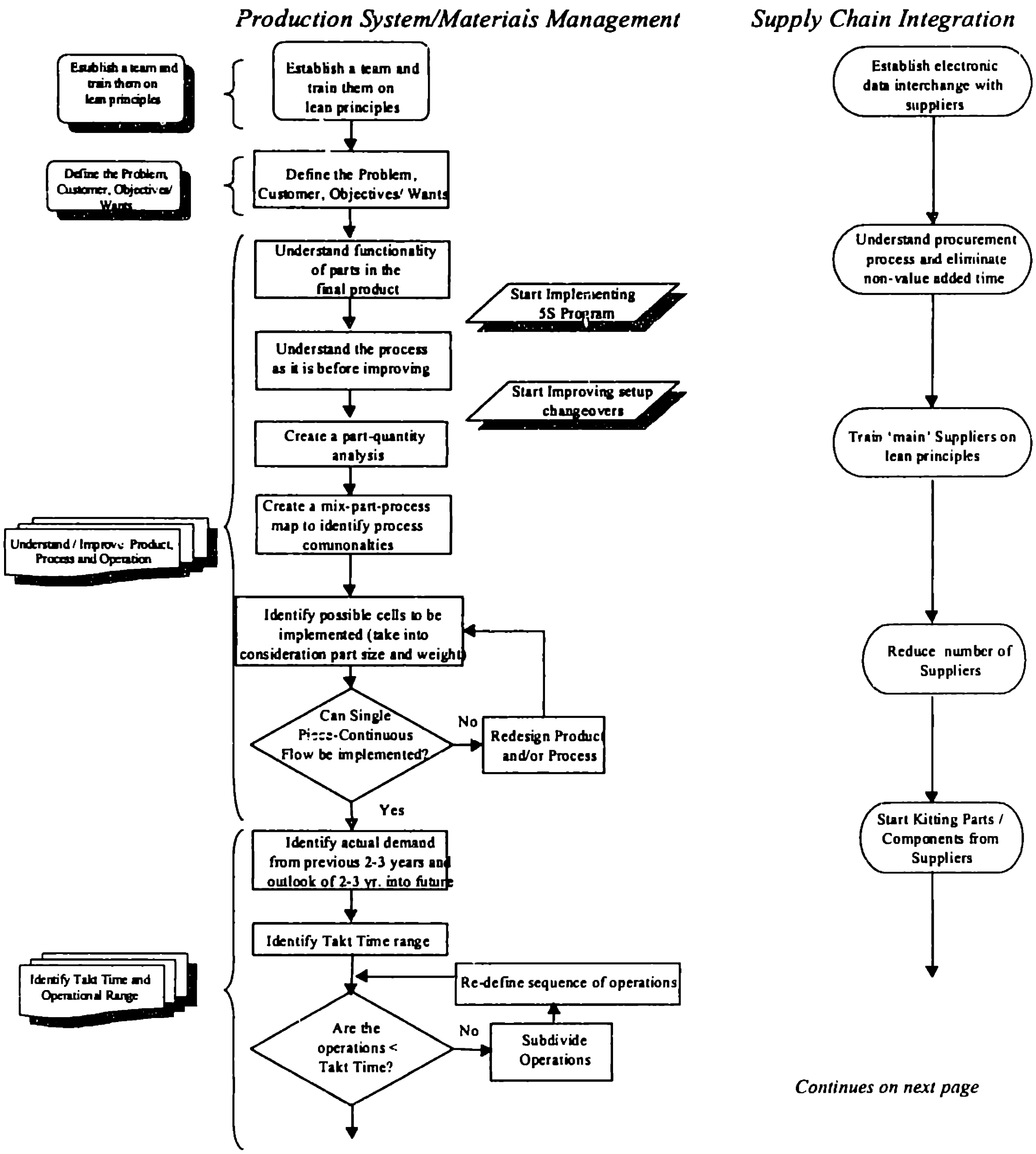


Figure 8-27: Example of Table taken from Design for Manufacturing and Assembly to estimate Manual insertion time [Boothroyd, Dewhurst, 1982]

8.4 Converting an Existing Machining System

Most of the time when a fabrication area (machining) needs to be improved requires converting systems that were fashioned with a job shop mentality (departmental layout) to a system that supports the lean production system design principles. Many companies have placed constraints on the system because of part characteristics (size, weight, etc). However, we saw in previous chapters that the concepts of lean production (minimum takt time, balanced, level, predictable output, and minimum operating cost and investment) can be applied whether the part being machined is small or large part, heavy or light (i.e. blade and aircraft engine casing). The system design difference is the time it takes to machine the part for each operation and the method used for material handling. At the same time, the takt time for larger parts is much lower because of lower demand. For example, a turbine blade is a small part and the takt time is around 10 minutes. On the other hand, an aircraft engine seal or casing is a large part (2-5' in diameter) would take several hours to be machined; however the takt time for that part is also in the range of hours (~ 15-20 hours).

At the macro level, the methodology is exactly the same as the one depicted in figure 8-4. The process to convert an existing assembly system and machining system to systems that support the "lean production system" concepts is very similar also at the micro or detail level. The main differences are during the formation of cells or flow lines. The next sections only address the steps that have not been explained in previous sections. Figure 8-28 shows the steps necessary to convert an existing machining systems to one that espouses the lean production characteristics.



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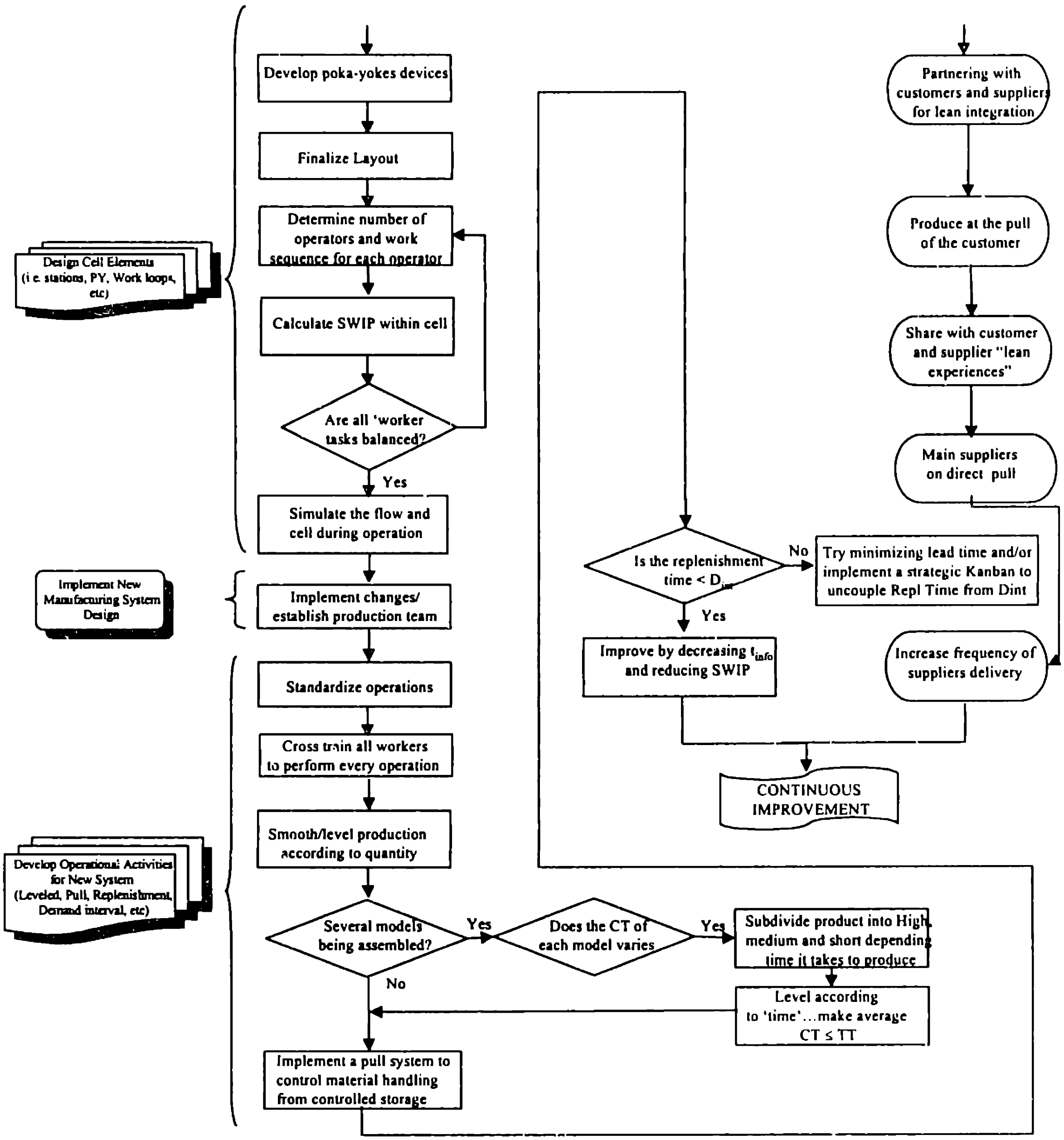


Figure 8-28: Designing Existing machining system (detail methodology)

From the figure above, it can be seen changeover reduction and implementing a *5-S* program needs to be done concurrently with the other steps in the process. The *5-S* program was explained in section 8.2. Shigeo Shingo developed a four conceptual stages to achieve "Single Minute Exchange of Dies" (SMED), which is a procedure to minimize changeover time. The four stages of SMED are [Shingo, 1989]:

Stage One: No distinction between internal and external setup. Internal setup are the operations that can be performed only when the machine is stopped, such as mounting or removing fixtures. External setup are the operations that can be completed while the machine is running, such as transporting dies to or from storage.

Stage Two: This stage involves the separation of the external and internal setup operations.

*Stage Three:*During this stage, the operations are analyzed to determined whether any of the activities conducted as internal setup can be converted to external setup. For example, preheating a casting die while the machine is still running eliminates the need for preheating with trial shots of molten metal during internal setup.

Stage Four: Examine both internal and external setup operations for additional improvements. Eliminate adjustment or streamlining clamping methods (clamping without screws).

8.4.1 Create a part-quantity analysis

A part-quantity analysis must be done to analyze the relationship between products and production output. This will help in the evaluation of the products being produced and how can they be combined to create cells.

Once the product-quantity analysis is done, the products can be broken down into three categories: A, B and C. Category A are parts that comprise 80% of the volume but are only 20% of total parts. Dedicated lines can be appropriate for parts under category A. Category B and C parts are parts that can be made in a line or cell that produces different parts with similar process paths and can therefore use the same line configuration.

Dedicate most effort to the parts under category B and C. If there are many parts in the machining area to study (~ 500-1,000), the team must try to determine which parts are most convenient to implement a cell. The team must also remember that they must analyze the parts before deciding for a specific group of parts. For example, a small machine shop company in the New England area wanted to convert to a leaner environment. Since this company was machining more than 500 different part numbers, it was decided that the parts with medium/repetitive (group B) volume orders (~20-50 per month) should be studied to create a cell. After the parts were defined (~150 parts), the characteristics, routines and existing process were studied to understand the functions of the parts. In this case only around 80 parts were chosen as good candidates for an "interim cell". An interim cell is a group of machines arranged in a 'U' shape layout.

TOOL

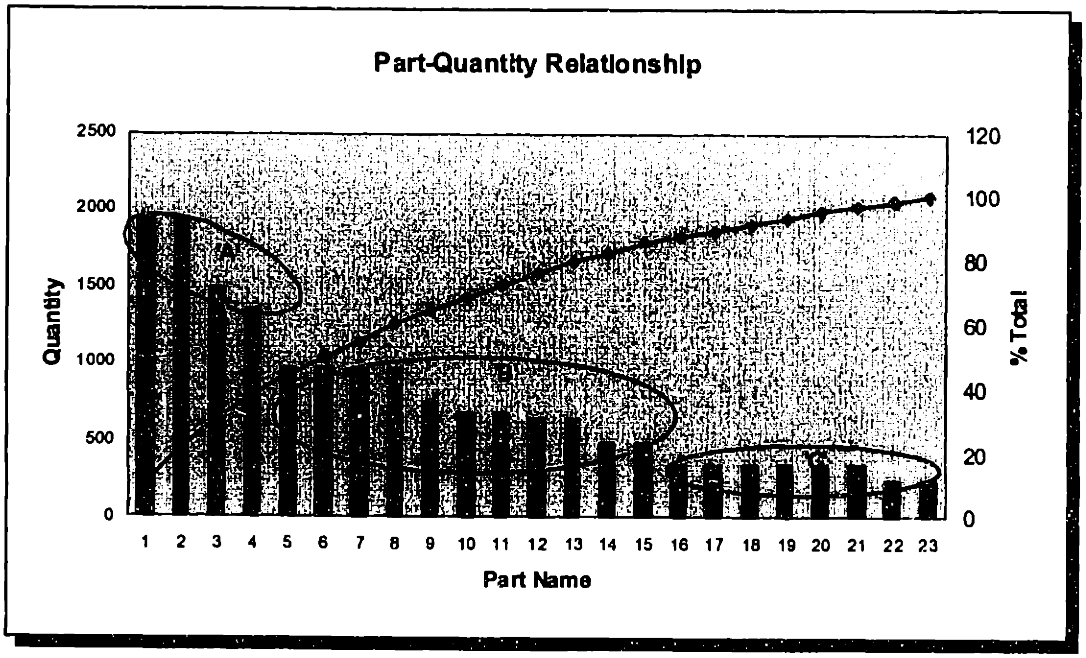


Figure 8-29: Part-Quantity Relationship

8.4.2 Create a mix-part process map to identify process commonalties

The purpose of this step is to establish the types of machines and other equipment that are needed for processing each part number and what path these processes take. A process matrix will highlight which parts should be processed together to match the flow of other parts.

TOOL

The chart not only shows a relationship of parts and machines but also shows the process the parts follow.

Product Name

Part Types		Operation	MACHINES								
			L1	Belt Sander	L2	Wheel grinder	S1	S2	S3	4SPD	D1
Part name 1(part number)		cut to size	X								
		round corners		X							
	**	WELDING (stud)									
Part name 2(part number)		cut to size	X								
		round corners		X							
	**	drill countersink								X	
	**	tap									
		WELDING (knob)									
Part name 3(part number)		precut									
		deburr			X						
	**	drill countersink								X	
		tap									

Figure 8-30: Mix-Part-Process Map

8.4.3 Identify possible cells to be implemented

With the help of the part quantity chart and the process matrix, the team should be able to start grouping common processes. Not only do the processes need to be studied, but also part characteristics like size, shape, material or any other critical features of the part. In some instances where machines or processes can not be grouped together, the team should study the possibility of creating product-focused cells. That is, cells that make different part types but all of them go to the same product.

8.4.4 Simulate the flow and cell operation

This is done to verify physically the flow of the cell and determine the correct machine layout before any movement of machines is done. This can be done by cutting pieces of cardboard equal to the footprint of the machine and laying them out like the cell and simulate the flow and movement of parts. Operators are key players on this task since they are the end users of the cells.

8.5 Designing a New Machining System

The process to design a new machining system is the same as the one presented in the section 8.3 (*Designing New Assembly System*) with the difference that the lower portion in Figure 8-31 is from the lower portion of Figure 8-28. Usually, the design of a new machining system involves the design of new machines or equipment. In this section, some guidelines will be developed to help a designer in the design of new machines or equipment to support the use of lean production systems.

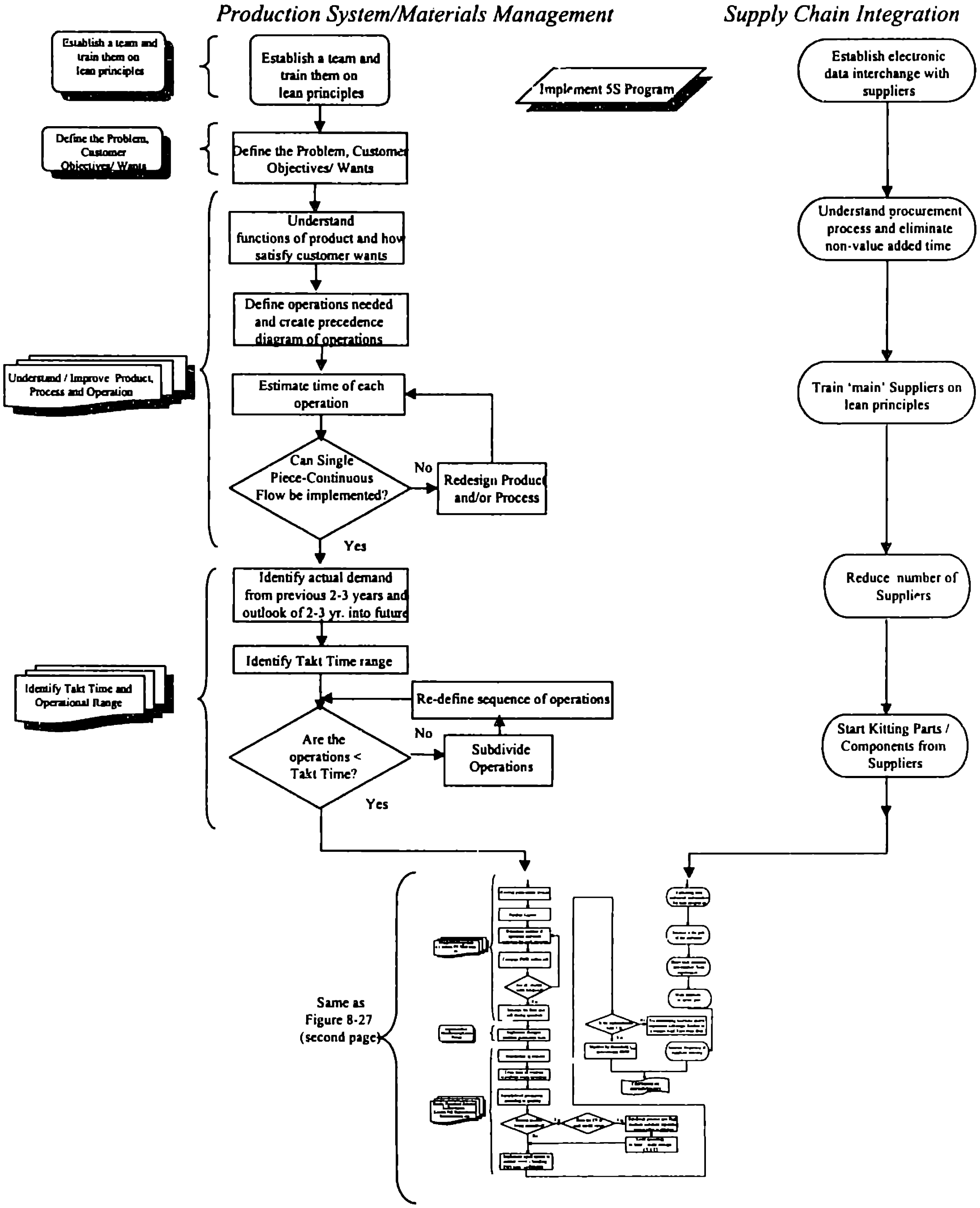


Figure 8-31: Designing New Machining System

When designing machines, the following criteria should be taken into consideration:

- Error-proofing built into fixturing and/or process (i.e. fixture to accept only a good part, color coding, visual or electronic means)
- Design based on preventive and predictable maintenance
- Integral frame

- Flexible utility drops
- Simple leveling system
- All shut-offs together
- Machines easy to move with fork truck
- Width of machines of 4'-5'
- Manual load, automatic unload. Operator performs the complex movements needed to load the part.
- Machine only performs linear motion movements to increase reliability
- General simplicity designed into entire machine (linear / 3 axis machines)
- Complexity in tooling, not in machine
- Machine easy to service from the back (Chips and coolant)
- Quick change tooling (<10 min) and interchangeable fixtures
- Flexibility rationalized with product requirements
- Quick release fittings
- Waist to shoulder effective work height
- Minimal reaching to load machine
- Use of walk-away switches to start cycle of machine

Figure 8-32 represents a drawing of machine that meet many design characteristics specified in the previous list.

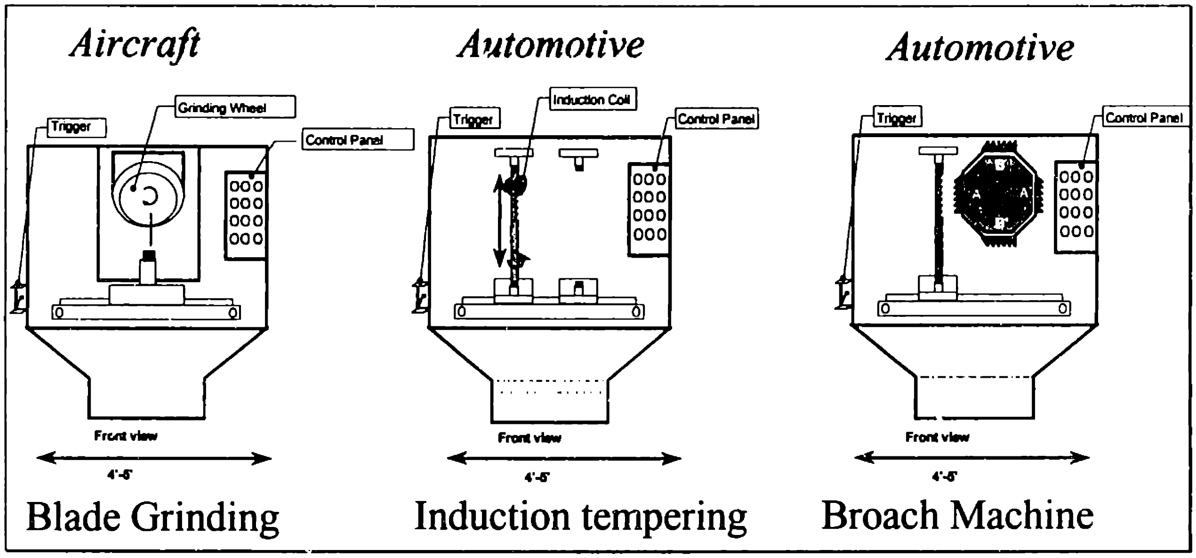


Figure 8-32: Typical Machine design whether aircraft or automotive

9

Case Study: Converting an Existing Low Volume/High Mix Company

9.1 Introduction

Company VRA is a relatively small company in the south Boston area with a total of 42 employees (Figure 9-1). VRA offers high performance Vibration Isolation Systems and Optical Tables to academic, industrial and government laboratories worldwide. The core competence is the manufacture of vibration isolating product components. The annual sales volume of the company is represented by more than 1000 orders per year on average.

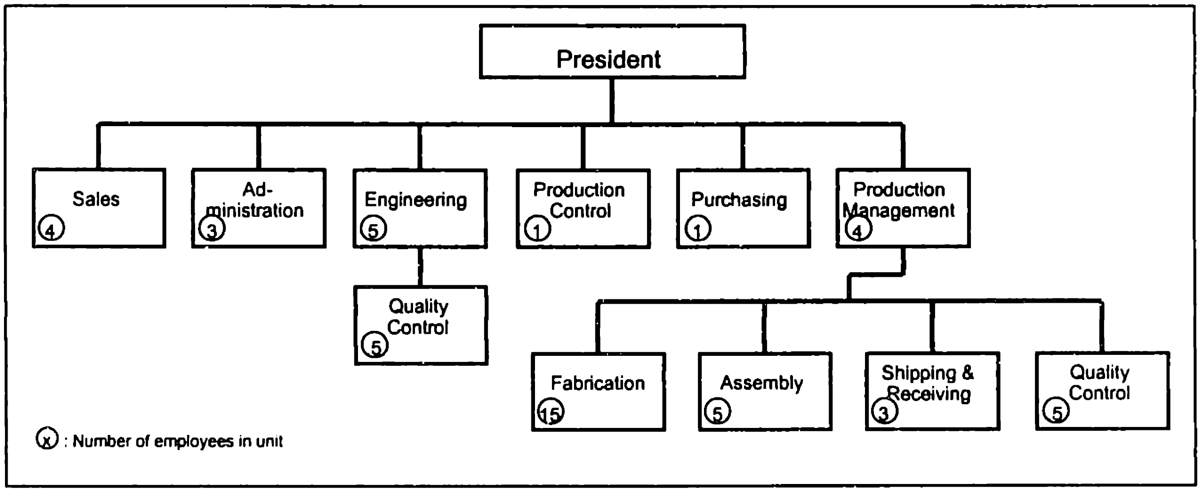


Figure 9-1: VRA Organizational Chart

9.1.1 Competitors and Type of market

VRA competes in two basic market segments:

a) Optical Tables: large Honeycomb Tables combined with Modular legstands. (5% market share)
b) Vibration Isolation Systems: smaller workstations such as 9100 and 1201 series (20% market share)

Both markets are shared with three other competitors located in the U.S. and Great Britain. VRA has customers in every major country of the world. The competitor's order lead-time is in the same range as VRA, which is 4-6 weeks (although it actually takes 10-12 weeks at VRA). The competitive advantage of VRA is based on approximately 5-10% lower selling prices and the ability to make non-standard, customized products. Customer demand is very unpredictable, has seasonal volatility, and is usually in small order batches.

9.1.2 Products and Plant Layout

Products in Company VRA can be classified into four main groups, which are:

a) Table Tops:
- Honeycomb Table Tops (core of corrugated metal stripes)
- Composite Table Tops (wooden core)
- Solid Steel Table Tops (solid steel core)
- Tables with counterweight (Benchmates)

b) Individual Airmounts and OEM
- Thermawave
- ESI
- 1206 Series

c) Support Systems:
- Optical Table Support Systems: Isolation or Modular Legstands (500 Series)
- Breadboard Support Systems: Isolation Legstands (9100 Series)
- IsoMate Support Systems (1200 Series)
- Benchmates (2200 Series)

d) Accessories:
- Auxiliary Work Surfaces
- Table Top Enclosures

- Laser Mounting Shelf

An example of Table Tops (a) and Individual Airmounts (b) is shown in the next figure.

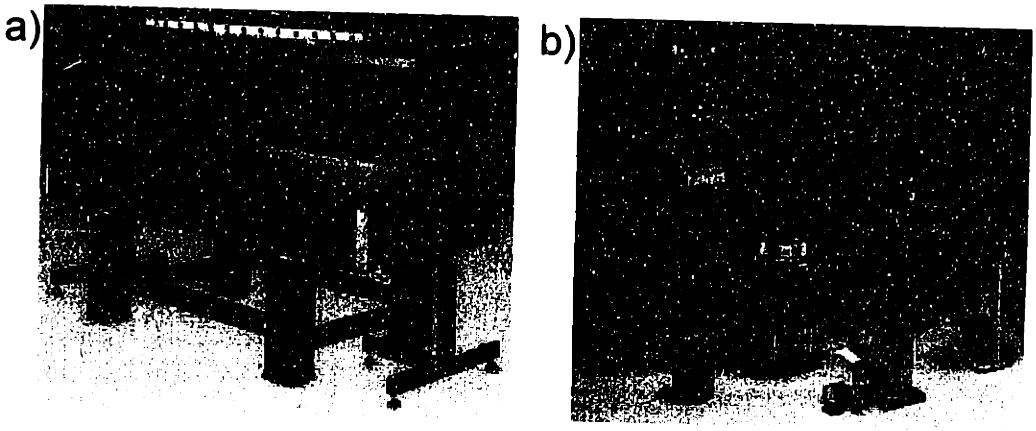


Figure 9-2: a) Table Top Equipment; b)Individula Air-mounts

The Company has 22,400 square feet of production floor space. VRA produces about 90 percent of components and table structures 'in-house'. In the figure above, VRA made every single part from cutting the legs to welding structure, to assembling the systems. There are six main departments: grinding, bonding, machining , assembly, carpentry, welding and shipping. A layout of VRA before any changes can be seen in the figure below (Figure 9-3)

The focus of this chapter are the ahcnges made to assembly and machining and how those two departments were redesigned to meet the customer demand rate.

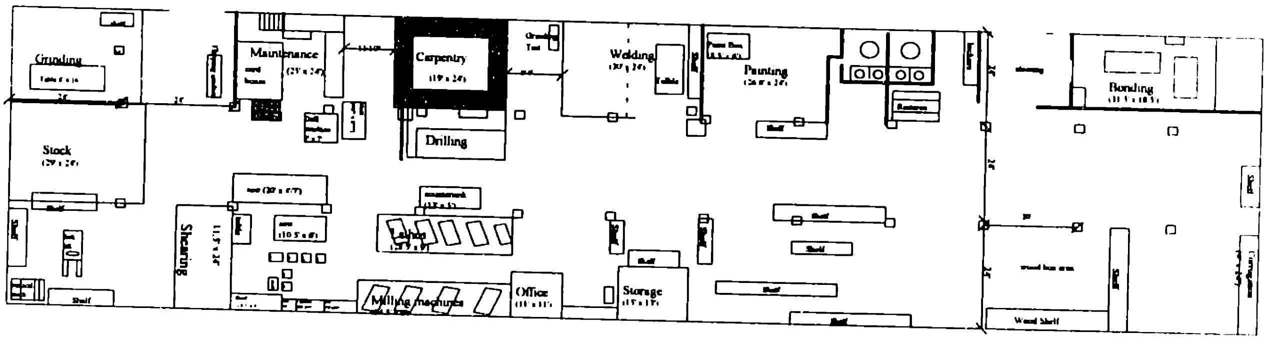


Figure 9-3: VRA before any changes made

The machine shop is a typical job shop layout, where the machines are grouped by function (Figure 9-4). Out of the 15 operators in fabrication (grinding, welding, carpentry, machine shop, etc) there are 5 operators dedicated to the machine shop. Operators can be considered specialists in what they do. They are dedicated to a department and can not switch from one department to another.

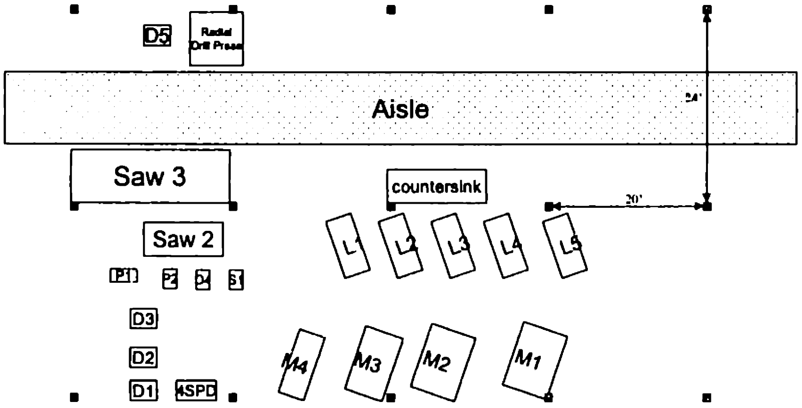


Figure 9-4: Job Shop Environment in the machining area at VRA

The assembly area is composed of many long tables. The operator has to find an empty are to work when he is assigned to assemble a product. All the material needed for assembly is kept in the storage room (Figure 9-5). There are a total of four operators in the assembly area. Before any improvements were made, the operators were product/component dedicated. Every day an operator works on the same product or component. If an operator is absent, then production of that product or component can not be done on that day.

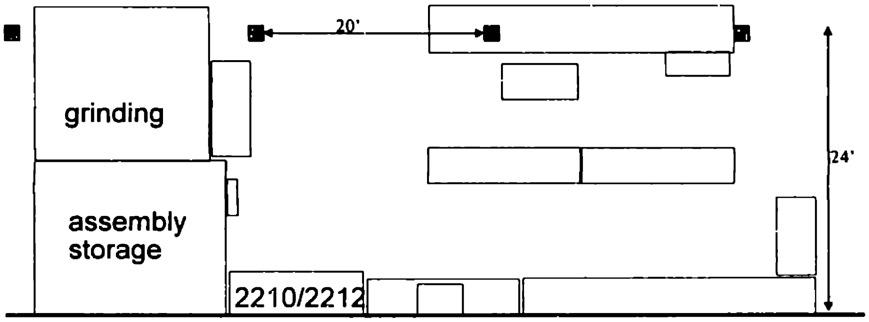


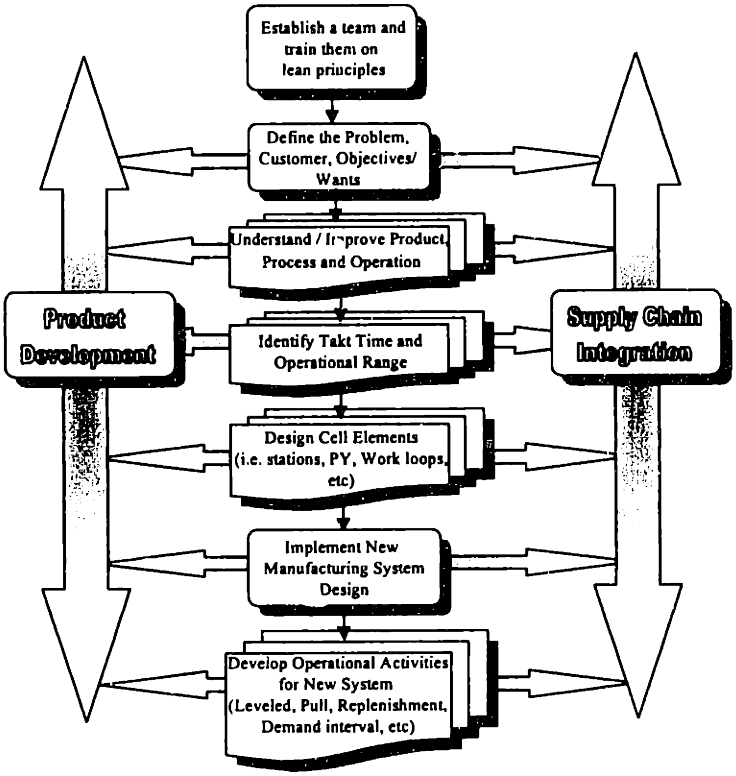
Figure 9-5: Assembly area is composed of many empty horizontal sufaces

9.2 Converting the Existing Assembly System

There are several consulting companies performing Kaizen events (improvement events) that take three to four days. In such Kaizen activities, a team tries to make specific improvements in a particular area. Out of the three-four days only one day is dedicated to training the team on some of the lean concepts. If the team involved in the kaizen event have never been trained in lean manufacturing concepts, one day is not enough to change the mentality of people that have been doing business differently for many years. If people in the team have not been trained before in lean concepts and do not *really understand* in detail the how's and why's of lean manufacturing, it would take several iterations and many improvement events to achieve the desired goal. Furthermore, if the mentality and thinking of the team is not changed entirely, the team must go back to the way they were doing business before. Experienced practitioners point out that with the three or five day *kaizen*, the job is never really finished [Sheridan, 1997]. This is why many companies that have adopted kaizen techniques deploy them over and over again –often revisiting the same area {Sheridan, 1997]. Maintaining the discipline to continuously improve is the biggest challenge and the most important aspect once a production system is in place.

Changes at VRA took more than three days. The changes done at VRA took three to four months of preparation (analysis of assembly and fabrication) and one week of shut down. The changes at VRA required this amount of time for several reasons. First, management was extremely reluctant to make changes in the manufacturing system and they thought that root cause of the problem was people and old machines, not the system. Secondly, about 65% of the employees have been with the company for more than 15 years, so they were used to the day-to-day problems and have never seen any improvement in their company (un-proactive mentality). Another reason is that VRA was the first company in the vibration isolation market and they did not want to accept that nowadays competition is taking their share of the market.

The flow chart presented in figure 8-5 was used to convert the assembly system at VRA from a batch and very unpredictable system to one that supports the concepts of lean production. The discussion in the sections to follow will be subdivided into the 'macro-levels' showed in the next figure.



Reprinted from 'Figure 8-4: Implementation Steps of a Lean Production System Design at a Macro-Level'

9.2.1 Establish a team and train

It was decided the members of the team would be as follows:

1. President (1)
2. Chief Engineering (1)
3. Purchasing (1)
4. Manufacturing Supervisor (1)
5. Assembly workers (2)
6. Machining workers (2)
7. Shipping (1)

At the beginning, the team was very reluctant to make any changes. An argument from the team was that lean manufacturing principles could not be applied to their industry because they are a low volume/high mix company and lean manufacturing could only be applied to the automotive industry, which is a high volume/medium mix industry. It took several meetings and a few days of training to convince the team of how the lean principles could be applicable in their industry too. Some training for the team was done at the beginning; however, training was an on-going activity.

9.2.2 Define the Problem, Customer and Objectives/Wants

Problems at VRA were the same as in any other large company. There were problems with management, engineering, product design and production system. When trying to define the problems in the assembly area, the team found that the problems were company wide and were the same in any department of the company. Some of the main problems the team wanted to be solved were the following:

- Management-operator relationship (no trust at all) operator yearly turnover of 40%
- Customer orders always late
- Unpredictable lead times
- Inconsistency on material flow and availability
- Administrative inefficiencies
- High levels of inventory
- Quality problems
- Competitors gaining market share
- No traceability of costs. VRA set the product's price to be 5-10% lower than the competitors regardless of the cost to manufacture it.

The team decided on various goals for the design of the new assembly area. The goals are as follow,

- Increase on-time delivery from 5-10% to 80-90%
- Lead time reduction from 10-12 weeks to al least 4-6 weeks and be very predictable
- Inventory reduction (at least 50% reduction of inventory (before changes ~4,000ft^2 of inventory distributed throughout the company)
- Space reduction as much as possible in order to introduce new products

- Reduce customer returns from 30-40% to less than 10%
- Minimize transportation

It is evident that all the problems mentioned above are affecting the buyer of the product, or external customer. Internally, the company is struggling to maintain operators working for more than one year. The worker fluctuation on the shop floor is comparatively high and accounts to a turnover of about 10 workers per year.

9.2.3 Understand/Improve Product, Process and Operations

From the assembly area, it was decided to start the improvements on the 9100 and 1200 series. These two series are very similar and are under the 'support systems' segment of the company. They account for 35% of sales in the company and that number is expected to increase (5-10%). The improvements to 9100 and 1200 series will improve indirectly the assembly of 1206 series and OEM products, which account for another 25% of sales. Therefore by improving the product lines mentioned (9100 and 1200 series) the company will be improving products that account for 60% of their sales.

The most important feature of 9100 and 1200 series is that it contains an automatic height control leveling system (Figure 9-6). This leveling system is composed of a servo valve system that feeds air from a pressurized air source or bleeds air from the legs, so that the isolated tabletop is conveniently maintained at a preset deflection level independent of load addition or removal. Precision can be obtained in the range of ±0.015" to ±0.0025" depending on the valve type. The most common isolation mount or system is composed of a level valve, a drop air mount, and a regulator.

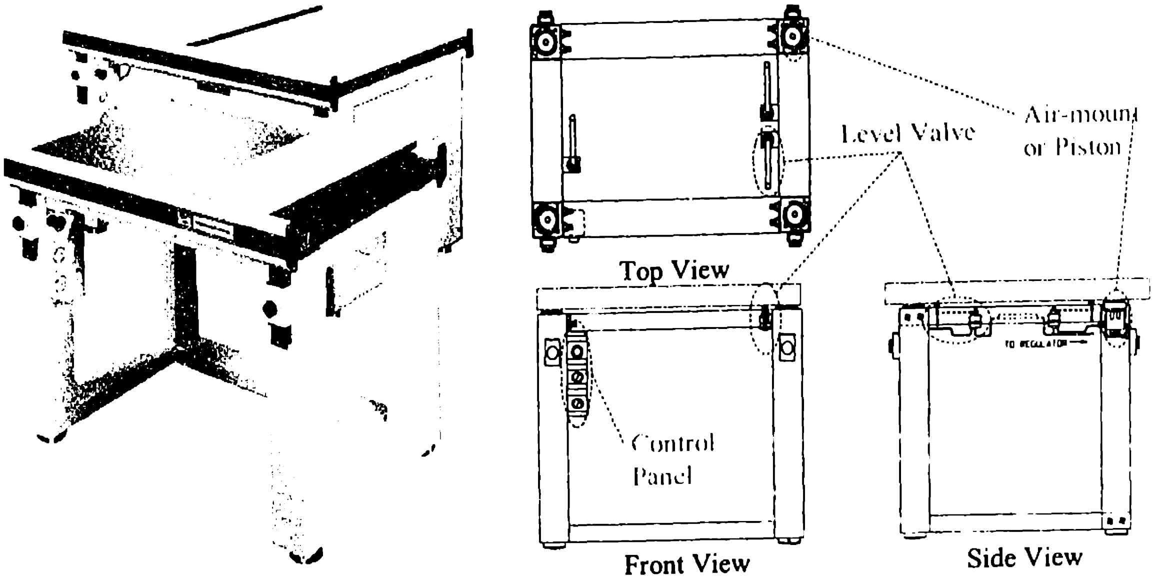
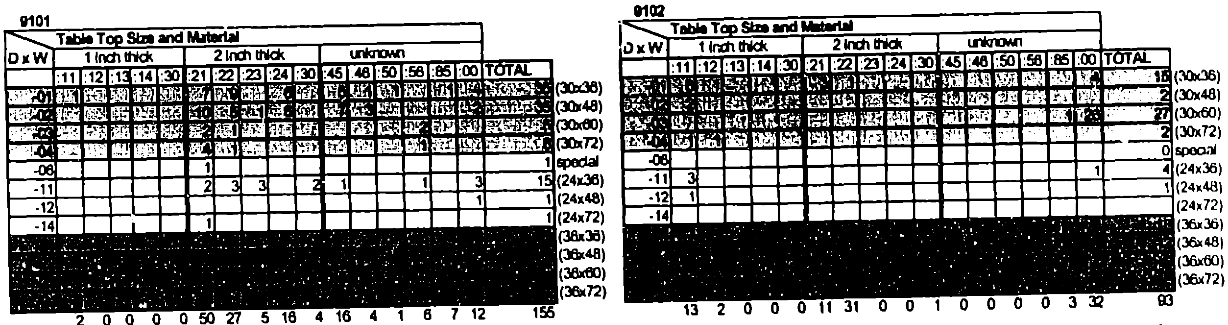


Figure 9-6: 9100 series

The 9100 and 1200 series have many possible combinations (from 7-12 different sizes). The distribution of the sales for the 9101 and 9102 according to the sizes can be seen in Figure 9-7. There are three main classifications:

- Standard Product (high demand)
- Standard Product (low demand)
- Non-Standard Product

The same three sales classifications can be obtained from analyzing the 1200 series.



9101

D x W	Table Top Size and Material 1 Inch thick :11	:12	:13	:14	:30	2 Inch thick :21	:22	:23	:24	:30	unknown :45	:48	:50	:58	:85	:00	TOTAL	
-01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	(30x36)
-02	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	(30x48)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	(30x60)
-04	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	(30x72)
-08						1											1	special
-11						2	3	3		2	1			1		3	15	(24x36)
-12																1	1	(24x48)
-14						1											1	(24x72)
																		(36x36)
																		(36x48)
																		(36x60)
																		(36x72)
	2	0	0	0	0	50	27	5	16	4	16	4	1	6	7	12	155	

9102

D x W	Table Top Size and Material 1 Inch thick :11	:12	:13	:14	:30	2 Inch thick :21	:22	:23	:24	:30	unknown :45	:48	:50	:58	:85	:00	TOTAL	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	18	(30x36)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	(30x48)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	27	(30x60)
-04	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	(30x72)
-08																	0	special
-11	3															1	4	(24x36)
-12	1																1	(24x48)
-14																		(24x72)
																		(36x36)
																		(36x48)
																		(36x60)
																		(36x72)
	13	2	0	0	0	11	31	0	0	1	0	0	0	0	3	32	93	

Figure 9-7: Distribution of sales volume of the 9100 and 1200 Series relative to specific legstand sizes.

Every component needed for assembling a 9100 or 1200 series is manufactured 'in-house' at VRA with the exception of Painting, which is outsourced because VRA is in a location where the Environmental Protection Agency prohibits the use of any paint chemicals.

There are seven main components in the 9100 and 1200 series (Figure 9-7 & 9-8), which are:

1. Level Valve
2. Air-mount (for 9100)
3. Control Panel
4. Piston (for 1200)
5. Table-top
6. Left-Side Weldment (two legs welded to a brace)
7. Right-Side Weldment (two legs welded to a brace)

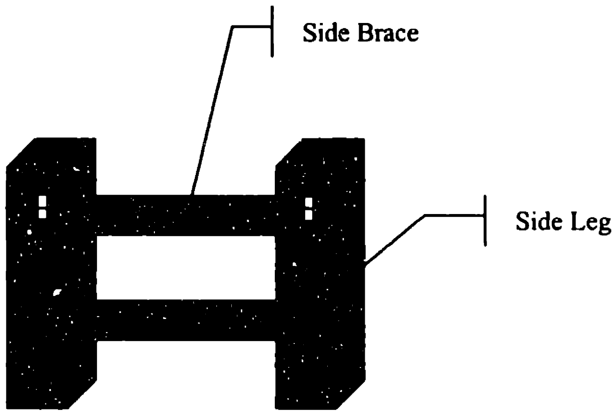


Figure 9-8: Typical 9100/1201 Leg Pair Weldment

Some components are unique and others are not. The level valve, air-mounts, pistons, regulators and control panel are used in most of the products made at VRA. The leg weldment (right and left) is the only unique component but it has more than 10 different possible combinations. Since the components are not unique to the final product, the team is thinking about the possibility of creating sub-assembly cells needed for each component.

Table 9-1 presents the components needed for the production of the 1200 and 9100 series.

Description	Part Number	Product
Level Valve		
	120497-1 to -15	1200
	123144-1	2212
	120938-1 to -2	9100
	120426-1 to -2	TW
Air-Mount		
200 lbs	123168-1 to -3	9101
320 lbs	123169-1 to -3	9102
	123126-1 to -3	2210-2212
C. Panel		
	120935-0 to -1	9100
	123107-1 to -5	2210
	123095-1 to -5	2212
Piston		
	120002-1 to -7	1206
	120003-1 to -8	1201-1202
	500598-1 to -2	500

Table 9-1: Components needed in the 1200 and 9100 series

Once the components and its functions were well understood, the assembly process of the components was videotaped to understand more about the processes and operations before any improvement. The videotaped process was then analyzed and operations were divided into value added and non-value added. The categorization of operations into value and non-value added was performed with the operators and engineers.

Figure 9-9 demonstrates an example for analyzing a batch of six standard (high volume) level valves.

Step	Operation Element	Non-value added time	1	2	3	4	5	6
1	Look for Parts	540						
2	Prepare for first operation (Glue washers)	117						
3	Glue washers on arms		26	26	26	26	26	26
4	Prepare for second operation (inspection & cleaning of L.B.)	15						
5	Cleaning/Inspect lower body		3	2	4	4	5	5
	⋮		⋮	⋮				
44	Test valves		230	148	227	117	97	311
45	Fix defect valve (#3)				636			
46	Assemble knurled knobs into level arm. Insert plastic tip into knob		41	44	45	40	37	42
47	Walk/look around for valve's notebook and engraver machine	240						
48	Write down in notebook part # and valve #	95						
49	Engrave part # & valve #		38	29	32	32	29	30
	END							

Figure 9-9: Understangin the process to assemble level valves

The process was also mapped to determine the flow of parts and path of the operator. The valves traveled approximately 200-300 feet. Figure 9-10 demonstrates a part flow diagram of the level valve.

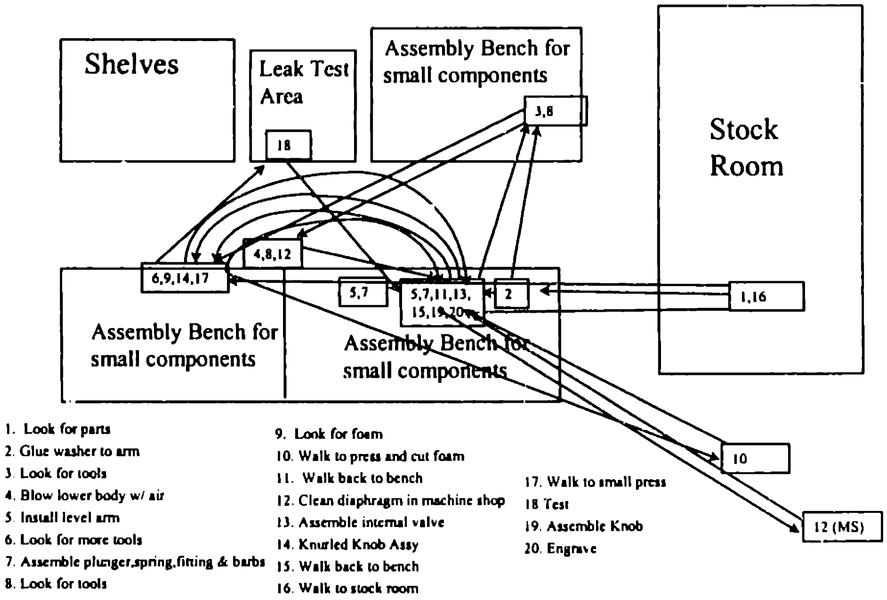


Figure 9-10: Process map of assembling level valves

For a non-standard level valve the situation is even worse. It took one operator almost six hours to assemble eight non-standard level valves. The only difference between a standard and non-standard is the orifice size on the inlet and outlet barbs.

From the previous analysis, it was decided that the components would be assembled in different cells. The components were grouped according to their functionality, part characteristics and process sharing. A model mix matrix was not done because the grouping of the components was obvious after the previous steps were done. The plan is to have one cell for the level valves, another cell for the air-mounts and pistons and a third cell for control panels, regulators and delco valves. These three cells will take care of all the components needed in assembly. In later steps we will determine if the cell can be implemented and if the subdivision made is the most efficient one.

The process maps and charts created during the previous step were studied in detailed (for final product and components). The non-value added operations were officially eliminated and the operations left were defined correctly. For example, in figure 9-9 (assembly valve process) there are 49 operations and 35% of the time it takes to assembled the valve is non value added time (looking for parts, preparation of material, looking for tools, etc). Not only there was many non-value added activities, but the variability within each operation is very large. For example operation # 44 "test valves" ranges from 97 seconds to 311 seconds.

Out of the 49 operations, 40 were eliminated. The other nine operations were explicitly defined and any machine or equipment needed was identified. The next figure represent the result of this improvement and identification of the correct operations. From the study performed on this valve, a new valve design was proposed that would eliminate at least 6 parts and decrease the assembly time by 50%. The design is currently under study.

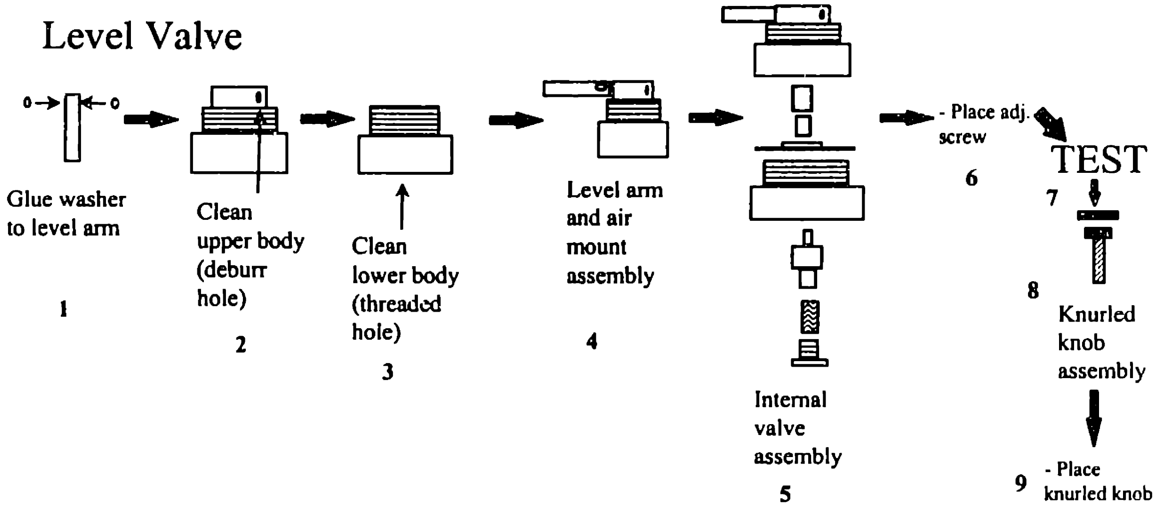


Figure 9-11: Proposed process to assemble level valves

For every component in the assembly area a new proposed process was developed as well as products in the final assembly of 9100 and 1200 products. When creating the new proposed porocess for assembling the components, the team ensured that single piece flow could be achieved in every operation.

9.2.4 Identify Takt Time and Operational Range

The calculation of the Takt Time range for the final assembly line was based on the two models identified previously (9100 and 1200). It was decided to design the cells with an extra 20% of capacity to allow for growth. This ensures daily production can meet daily demand fluctuations and also stimulates the sales department for getting more businesses. As seen from Table 9-2, the minimum takt time is 2.45 hours per optical table. This means that on the average, every 2.45 hours a table needs to be produced in the final assembly.

	Model	1995	1996	+ 20%
1200 Series	1201	174	145	174
	1202	18	25	30
9100 Series	9101	206	155	186
	9102	57	93	112
	9211	45	90	108
		500	508	610

Takt Time with 85% efficiency 147.24 min per table
2.45 hours per table

Table 9-2: Calculating the Minimum Takt Time

The same procedure was performed for the components and the following takt times were found:

Possible Cell	Minimum Takt time (85% eff) [min.]
Level Valve + T.W.	25
Air-mount + Piston	30
C. Panel + Regulator + Delco Valve	30

Table 9-3: Minimum Takt Time for proposed sub-assembly cells

It takes almost 2 hours to assemble a final optical table if all the components are available. The takt time for a table in the final assembly is 2.45 hours; therefore, the final assembly of an optical table can be done in less than the minimum takt time.

Operations performed to assemble the components needed for the optical table are also less than the minimum takt time. The next table shows an average cycle time from each of the cells and it can be seen that each cell cycle time is less than the takt time.

Possible Cell	Average Cell Cycle Time	Min. Takt Time
Valve + T.W.	20	25
Air-Mount + Piston	20	30
C. Panel + Regulator + Delco Valve	30	30

Time in Minutes

Table 9-4: Operation time < Minimum Takt Time

9.2.5 Design Cell Elements

From the previous step it was seen that the final assembly of an optical table could be done in 2 hours. Having all operations manual, the number of stations is obtained by

$$\text{Number of Stations} = \frac{\text{Manual Time to Assemble}}{\text{Takt Time}_{\text{minimum}}}$$

which in this case is equal to 1. This means that the final assembly of the table will be done at one location or station.

Manual operations were also combined into stations that would have a station time less than the minimum takt time. For example, the operations shown in Figure 9-1 were combined into one station because the manual time to assemble a valve is 12 minutes, while the minimum takt time for that cell is 25 minutes.

Every station was designed following the guidelines established in the previous chapter. Next figure demonstrates a graphic of a station used for assembling a level valve.

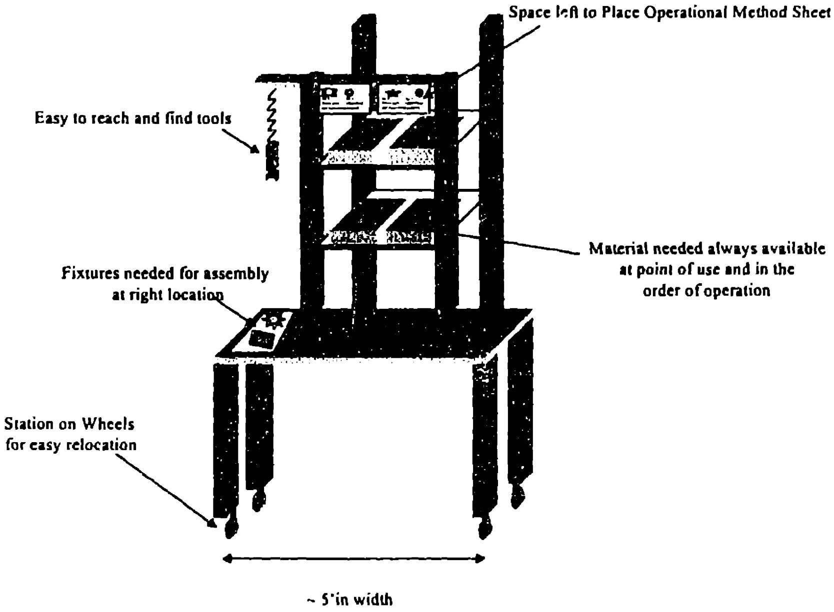


Figure 9-12: Typical station at VRA

An example of a poka-yoke design in the air-mount assembly station is a torque adjuster placed on the power tool. The tool will screw the bolt until the specified torque has been reached. Once the necessary torque has been applied the power tool will not apply more torque on the bolt.

Once the station and operations were well defined, the layout of the cell was finalized. It was decided to have each component made in a separate 'cell' and all of them to feed final assembly. Some of the reasons for doing this were to keep product families together, have all the material at the point of use to decrease the logistics of controlling production and decrease duplication of tools/equipment. Figure 9-13 presents the new layout of assembly. There are three sub-assembly cells making the different components needed for final assembly. Each sub-assembly cell is composed of two main stations, where different products can be made.

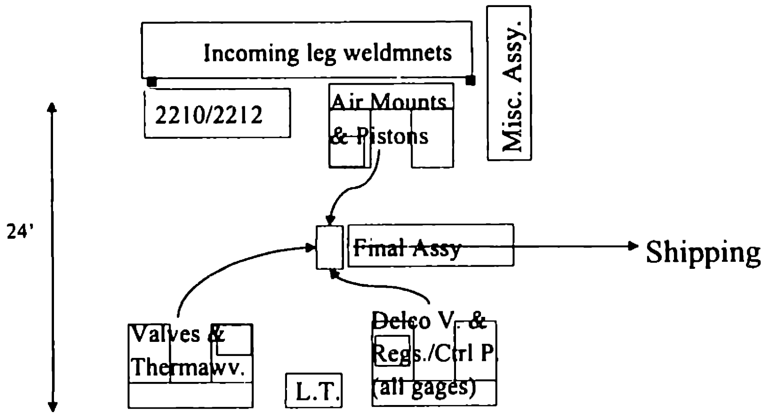


Figure 9-13: Semi-Fish-Bone layout

The number of operators was calculated using the following formula:

$$\text{Number of Operators} = \frac{\text{Manual time} + \text{Walking Time}}{\text{Takt Time}}$$

The total number of operators needed in the new assembly area is four (Table 9-5). Since there are 5 different cells, there will be three operators dedicated to a specific assembly, while one operator rotates between two cells. The operator that rotates is in charge of 2210/2212 cell and the Air-MT/Piston cell. The team thought about moving the 2210 and Air-MT cells closer or combining both cells, but this was not feasible. The 2210/2212 cell is the final assembly for the benchmates (another VRA's product) and because it needs some special equipment, could not be moved closer to the other cell or combined with the other cell. However, the cells were moved as close as possible to each other to minimize walking time.

Takt Time used to calcualte the number of operators is not the minimum takt time but the actual takt time for a month. In other words, the lines are designed based on the minimum takt time but ran at the actual takt time, which in this case is set to be re-calculated every month.

Cell	Average Manual Work Time (min)	Actual Takt Time (min)	# of Operators
Final Assembly	120	160	0.8
Valve + T.W.	20	30	0.7
Air-Mt + Piston	20	36	0.6
C. Panel + Regulator + Delco	30	35	0.9
2210/2212	100	181	0.6
		Total	3.6 → 4

Table 9-5: Calculating number of Operators needed in assembly

Since all worker tasks were balanced in the cells designed, there was no need to redefine or redesign any process or operation.

9.2.6 Implement new manufacturing system and establish production team

Before implementing the changes, the assembly area was cleaned and re-painted. Old equipment was also cleaned and re-painted. The idea was to create a better system to obtain higher productivity gains and to design a new environment for the benefit of the workers.

The new system needed also a new worker organization. The assembly area has now a team leader, who is in charge of material handling, supervising daily production, finding root cause of non-conformance material or products and replace any absent worker.

9.2.7 Develop Operational Activities for New System

Operations were standardized and operational method sheets were created. These sheets were posted on each station for the operators' use. Next figure shows an example of the operational sequence sheet placed on the valve assembly station.

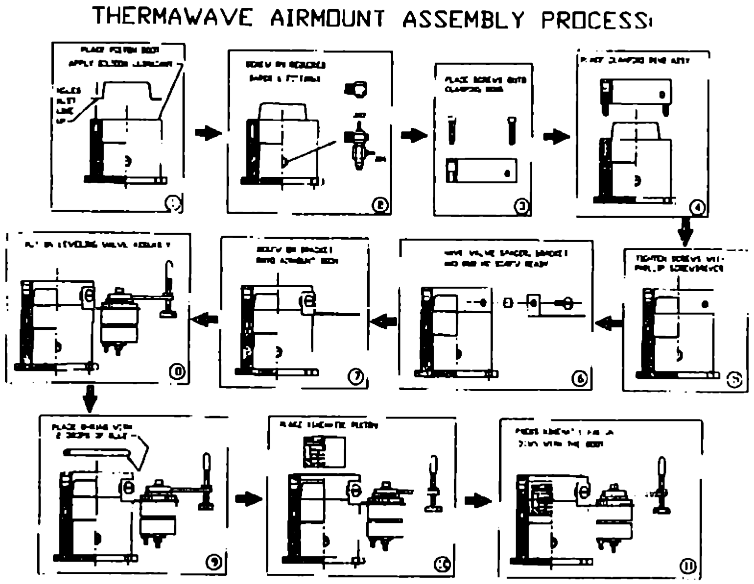


Figure 9-14: Example of Operational sequence sheet posted in the cell

Operators are now cross-trained between cells. Every operator in assembly needs to know how to assemble all components in the assembly area. The next step is to cross train operators between departments (i.e. machine shop and assembly).

The next chart shows a 'pie-chart' to demonstrate the skills of each operator within assembly.

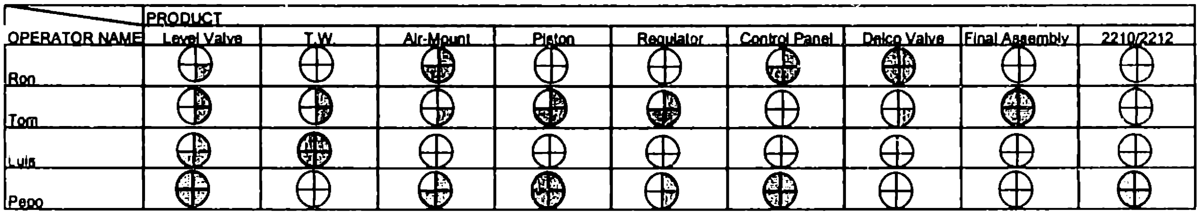


Figure 9-15: Pie-chart to demonstrate operator's training

Production is leveled on a weekly basis according to quantity. Every Friday, the production for the following is frozen to level and schedule accordingly. The team chose weekly intervals to minimize order lead time and make it more predictable. In later steps it will be seen that demand interval is chosen to be one week because of competitors lead time and customer demand for standard products.

There are at least three different models assembled in every cell and final assembly line. However, the time to assemble the models within the cells does not vary much. For this reason, leveling according to time is not necessary.

The material and components in the final assembly were subdivided into three categories. The three categories are:

1. Parts/Components made in-house
2. High value parts
3. Low value parts

Since VRA is in the make-to-order business, the components made in assembly were divided into standard and non-standard categories. The standard size of components made 'in house' (sub-assembly) are controlled with a kanban system. The signal to produce more components is an empty container (Figure 9-16). The non-standard products are signaled with a work order coming from production control. The work order is placed in the respective cell and the parts are made on a first-in-first-out basis. If there were any changes in the prioritization, the person in charge of production control could make the changes in the morning production meeting.

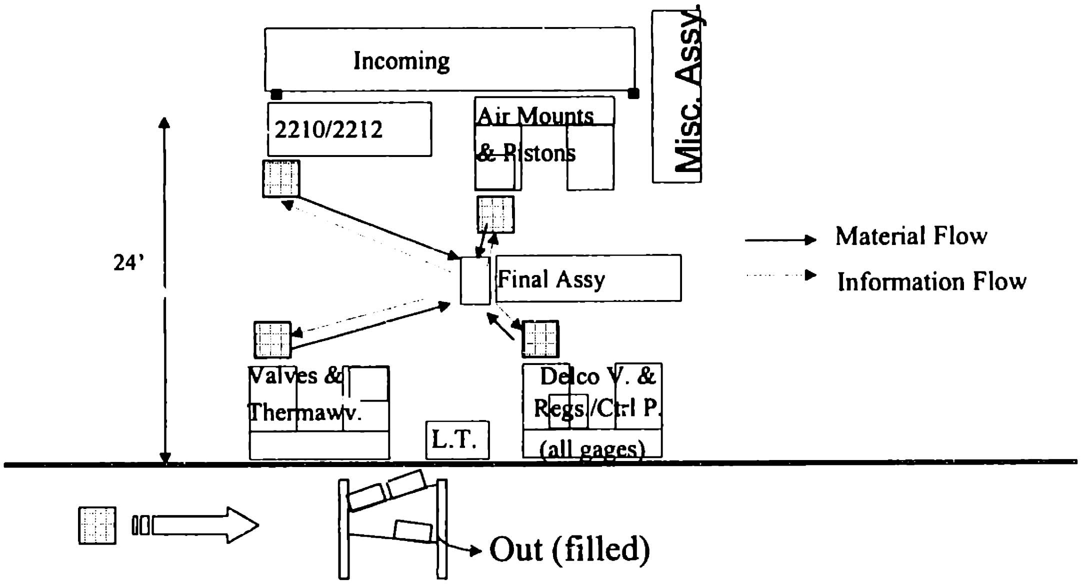


Figure 9-16: Kanban System implemented to control production of componets

The quantity of low value items was determined based on the economic order quantity from the source (EOQ). Sometimes the EOQ was 1,000 (i.e. bolts) making it impossible to place all bolts in the cell. For this reason a common replenishment location was establish with a two bin container located at the point of use in the cell. As soon as a container is empty, the container will be taken to the replenishment area by the team leader and filled, while the operator continues working with the second container. Meanwhile in the common replenishment location, as soon as the quantity of a part reaches its minimum allowance, a card taken from that container will be placed on the "supplier kanban post". The person in charge of purchasing will pickup the cards which states the type and quantity of material to be ordered.

The number of production order kanbans or kanban between assembly and sub-assembly was calculated using equation 5.4 (reprinted from Chapter 5):

$$\begin{array}{c}\#\text{ of }SWIP_{\text{between cells}}\\ \text{or}\\ \#\text{ of Production-Ordering Kanban}\end{array} = \frac{\text{Average Daily Demand*(Lead Time)*(1+safety stock)}}{\text{Container Capacity}} \quad (5.4)$$

The ideal situation for high value items would be to place them on a true pull system with the suppliers. However, in this case the pull with the suppliers could not be achieved due to contraints set by suppliers. Even though the pull system could not be implemented, the policy for buying supplied parts was modified. Before changes were made, VRA's suppliers were delivering parts to VRA in fixed quantities and intervals set by the supplier. Currently, VRA established an ordering system, with one of the major suppliers, (injection molded parts) to create a blank order and supply in a need-basis only. The blank order means that VRA can change the quantity and frequency (within the constrain of the supplier's lead time) of parts bought by VRA.

Since components and final product are being assembled at one location (one stations), meaning that the product or component does not move from station to station, there is no need for additional standard-work-in-process (SWIP) within the cells.

Since the customers' orders are in small batches and the demand is seasonal and volatile, the demand interval could not be obtained from one customer. For this reason, the customer wants for the 9100 and 1200 series were studied and found that customers buying this product wanted to have it as soon as possible and at a low cost. Customers with those requirements were also buying standard products (not customized).

It was found also that the competition was offering a similar model with lower lead time. For example, lead time for a 9100 at VRA was 4-6 week, while lead time at Competitor X was 2-4 weeks. VRA was better on cost compared to their competitors and wanted to gain more market share by decreasing their order lead time.

To uncouple the response time (4-6 weeks) from the replenishment time (Figure 9-17), it was decided to place a kanban or SWIP quantity after painting. In this manner, response time equals the assembly time plus shipping time and delivery time, which is less than one week (Figure 9-18).

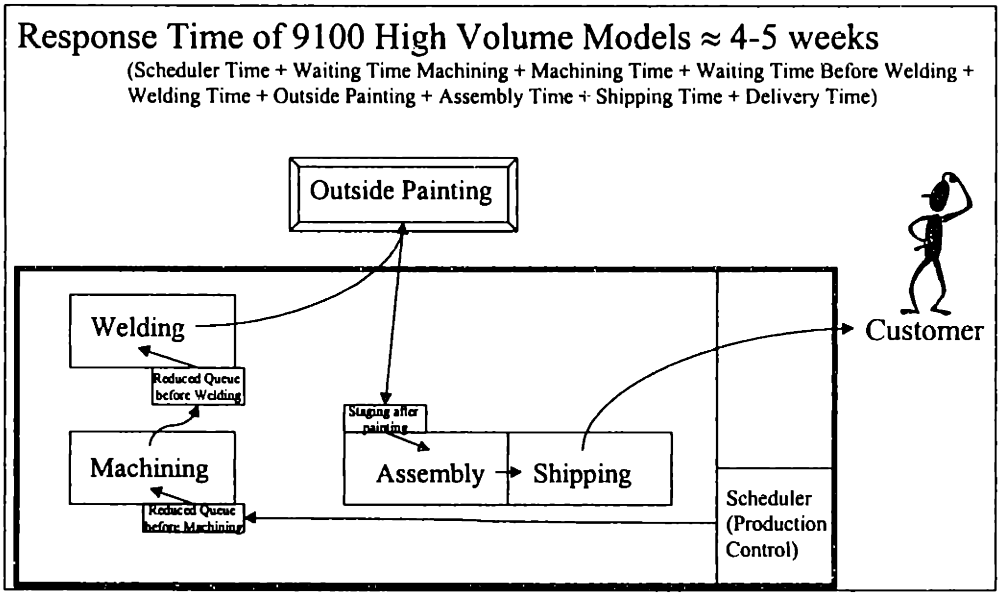


Figure 9-17: VRA before implementing kanban to uncouple response time from troughput time

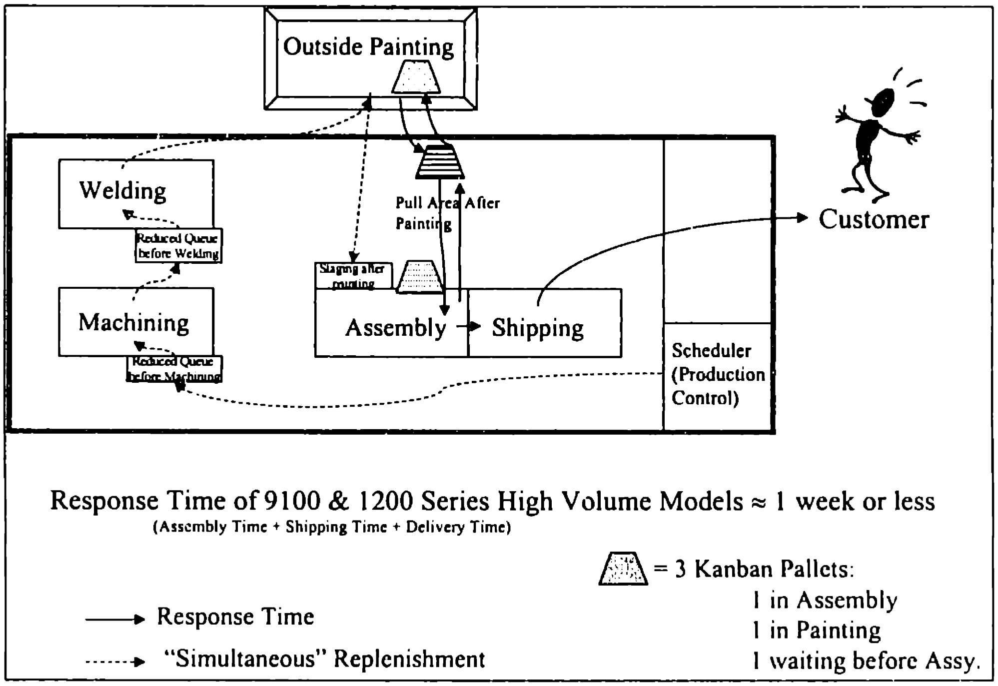


Figure 9-18: implementing a Kanban system to uncouple Response time from Replenishment Time

It was calculated (Table 9-6) that three kanbans were needed in front of assembly to have a response time of one week on the standard/high frequency products. At any moment in time, there would be one kanban in assembly being used, another in painting being filled and the third kanban would be waiting in front of assembly.

Data for One Leg Weldment

Machinining Time	40	min
Welding Time	70	min
Waiting Before Welding	690	min
Outside Painting Time	2300	min
Scheduler Time	690	min
Waiting before Machining	1380	min
TOTAL LEAD TIME	5170	min

Safety Coefficient	20%	
Container (skid) capacity	6	wldmts/skid

Days Waiting Before Welding	1.5 days
Days Waiting for Scheduler	1.5 days
Days Waiting Before Machining	3 days

30" depth Weldment	
ADD based on Don	1 units/day
ADD based on 1996 sales	1.20 units/day

ADD = Average Daily Demand

$$\# \text{ of Kanbans} = \frac{\text{(ADD)x(Lead Time)x(1+Safety Coefficient)}}{\text{Container Capacity}}$$

# of Kanbans (FOR 30") = 2.25 ——▶ Round to 3 Kanbans

OR 3 PALLETS CONTAINING
6 WELDMENTS EACH PALLET

Table 9-6: Calculation of number of kanbans in front of assembly.

9.3 Converting the Existing Machining System

The fabrication area is composed of welding, shearing, grinding, bonding and machine shop. The focus of this section will be on the machine shop. At the end of the section examples of improvements in other fabrication sections of VRA will be shown.

9.3.1 Team Training / Problem Definition / Operation Improvement

The machine shop and assembly were both analyzed at the same time; therefore, the same team was used for the improvement of assembly. The improvements and study started in assembly but when the company shut down for one-week changes were done company wide.

Assembly and machining were performing equally poorly. Problems in machining were the same ones described in the assembly (section 9.2.2).

All parts going through the machine shop were studied to understand its functionality once integrated in the final product. This step is very important because even though the company is relatively small, many machinists did not know the end product. By analyzing the functionality, operators realized the importance of many part characteristics.

Although it was very difficult because parts were machined in batches of 20-100 parts, every part was studied from start to finish to have a clear idea of perturbations in the process. The next figure demonstrates an example of the step by step process to make a leg weldment for the 9100 series.

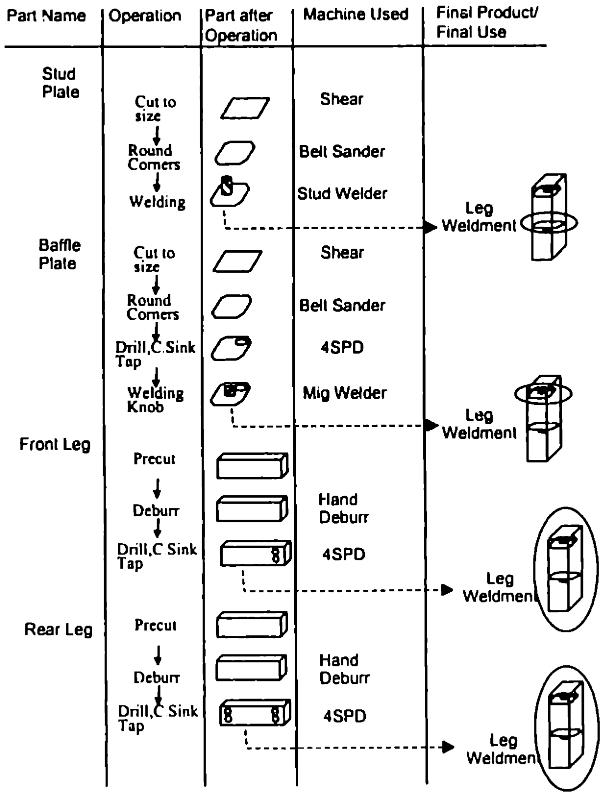


Figure 9-19: Example of the process map done to study/analyze parts made in the machine shop

The process of making a leg weldment was also mapped. It was found that the parts to make a weldment travel almost 1,000 feet. If we were to map the process twice the machines used would be completely different. The operators were using any machine available and then attempted to setup the machine according to their needs.

Every part made goes through a first part inspection and operators need to wait for the 'one' quality inspector to inspect the parts in order for the operator to continue. Because of the backlog in inspection, the operators would start another job while the inspector inspects the first part. Before the batch of parts is sent to another machine, the inspector would have to revise the batch randomly. The inspector not only has to inspect the parts made in machining, but also needs to inspect incoming parts, parts made in welding, parts coming from painting, etc. Sometimes parts wait to be inspected for days or even weeks. VRA knew about the inspector being the bottleneck of the process in many instances, but since there was no trust in the operators, management did not consider another option. Operators are now in charge and responsible for machining and inspecting every part they make.

A part quantity analysis was created to analyze the relationship between products and quantity of parts made in the machine shop. As seen from Figure 9-21, the first four parts comprise for almost 70% of the volume. From the study performed in the previous step, it was determined that these four parts needed at most two machines (belt sander, drill press) requiring less than five minutes to perform the operations needed. Therefore, these parts will be produced in dedicated machines. For the rest of the parts, a mix model map could be made to identify any common processes and/or families of parts.

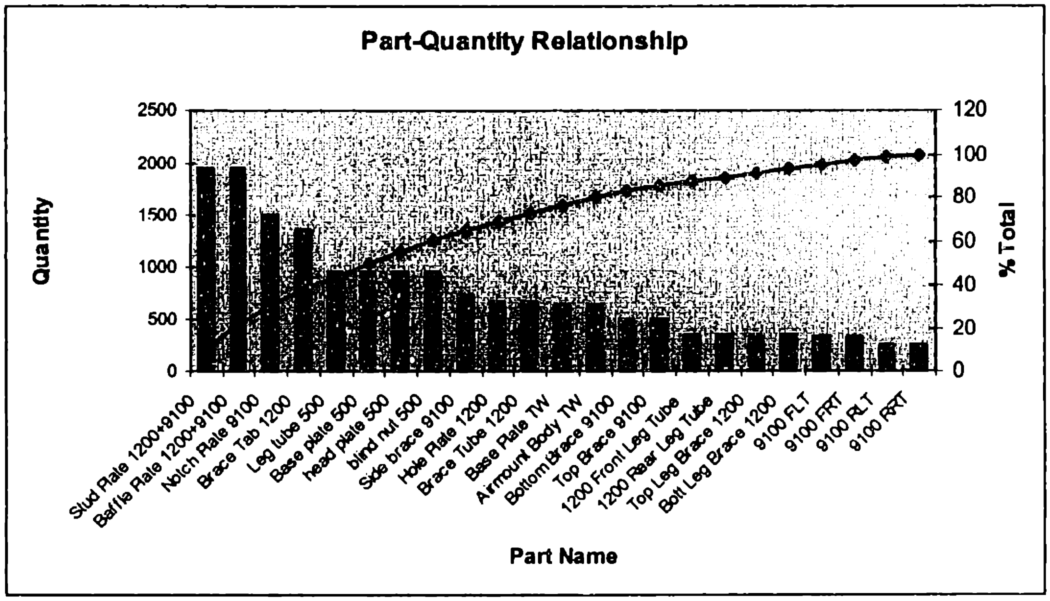


Figure 9-21 Part Quantity Relationship of the Machine Shop at VRA

Figure 9-22 represents a typical part-mix matrix created for the parts made in the machine shop. With this matrix, the team could highlight which parts should be processed together in a cell and which parts should be reprocessed in order to match the flow of parts. Notice also that welding is included in the matrix because one goal of the team was to incorporate welding into the cells.

			Shear	Belt Sander	Hand Deburr	Wheel grinder	S1	S2	S3	S4	4SPD	D1	D2	D3	D4	M1	M2	M3	M4	Tig	Stud weld	Mig	L1	L2	L3	L4	bend machine	P1	P2
Stud plate (120908)																													
		cut to size	X																										
		round corners		X																									
	**	WELDING (stud)																			X								
		LEG WELDMENT																											
Baffle Plate (130056-01)																													
		cut to size	X																										
		round corners		X																									
	**	drill,countersink,tap									X																		
	**	WELDING (knob)																				X							
		LEG WELDMENT																											
Front Leg (left & right) (B130054)																													
		precut																											
		deburr			X																								
	**	drill,countersink,tap									X																		
		LEG WELDMENT																											
Rear Leg (left & right) (B130051)																													
		precut																											
		deburr			X																								
	**	drill,countersink,tap									X																		
		LEG WELDMENT																											
Guard rail adj tube (120945)																													
		cut to size							X																				
		deburr			X																								
	**	drill,countersink,tap									X																		
		press bushing																										X	
		WELDING (bushing)																											
		retap (bushing)											X																
		LEG WELDMENT																											
LEG WELDMENT(FL,FR,RL,RR)																													
	**	weld baffle plate																				X							
	**	weld stud plate																				X							
	**	weld guard rail adj tube																											
	**	weld studs																			X								
		GRINDING																				X							
		LEAK TEST																				X							

Figure 9-22: Part-Mix-Model Map

Another goal is to minimize transportation and create an easier environment to control and schedule the production of parts. For this reason the team was aiming to create a cellular environment, where machines were close to each other and one operator could make the part in a single piece continuous flow.

A second part quantity chart was created to have a clear understanding of the parts that comprise 83% of parts made in the machine shop (the other 17% are the four parts identified previously). From the second part quantity analysis (Figure 9-23) and from the mix-matrix, it was decided that two groups could be formed. Both groups represent about 50 percent of the part quantity made in the machine shop. Group #1 is composed of the square cross sectional parts which are the parts needed for the 9100 and 1200 series, while group #2 are the circular cross sectional parts and OEM products.

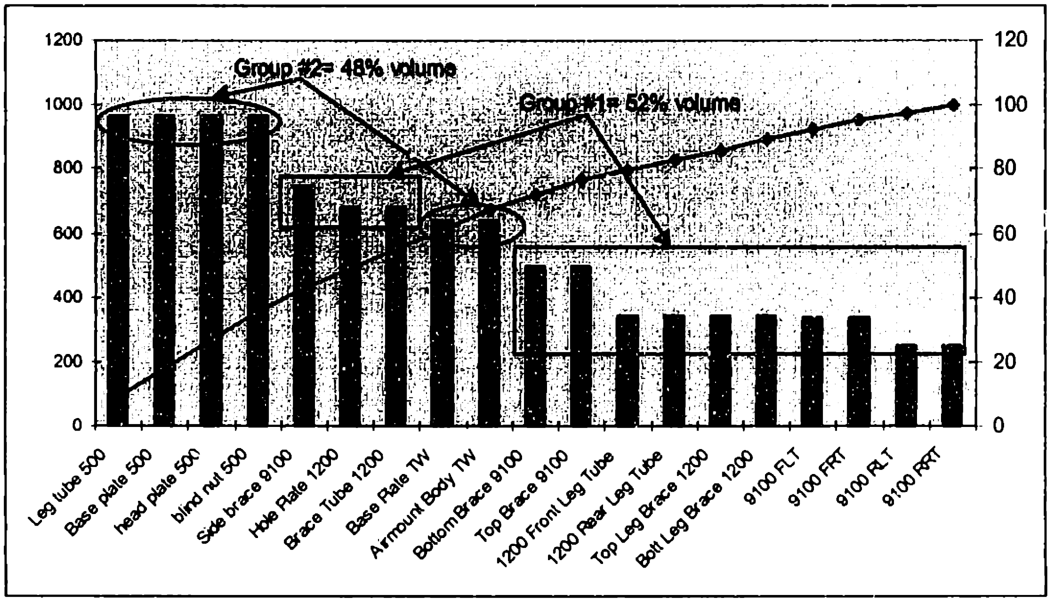
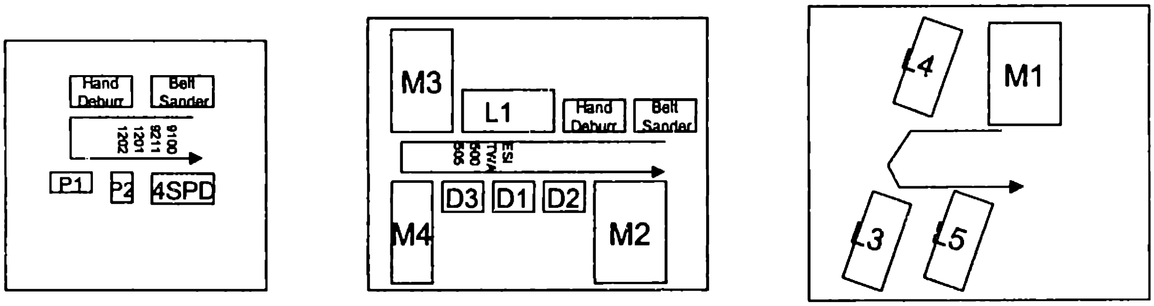


Figure 9-23: Defining possible cells in the machine shop at VRA

Three cells were identified during this step. One cell was identified for each group determined in figure 9-23. A third cell was created for parts that go directly to the assembly. The next figure represents the layout of the possible cells to be implemented. The next steps are checkpoints to determine if the cells could be implemented and would meet the objectives specified at the beginning.



Cell for Group 1

Cell for Group 2

Cell for Small Parts Going to Assembly

Figure 9-24: Possible Cells Identified at VRA (machine shop)

9.3.2 Identify Takt Time and Operational Range

The minimum takt time was calculated for each of the possible cells. Table 9-6 shows the minimum takt time for cell 'group #1'.

Description	Part Number	Max Yearly Usage from '95, 96	Minimum Takt time (85% eff) [min.]
9100			
FL & FR Leg Tube	130054	590	182.6
RL & RR Leg Tube	130053	590	182.6
Stud Plate	120908	1860	57.9
Baffle Plate	130055	1163	92.6
Bottom Brace	120919	555	194.1
Top Brace	120906	555	194.1
Side Brace	120947	604	178.3
GR Adj. Tube	130069	1236	87.1
9211			
Side Brace Tube	124071	36	2992.0
Leg Tube	134053	36	2992.0
Brace Tab	120039B	767	140.4
1201			
Leg Tube	120997	940	114.6
Baffle Plate	120873	1008	106.9
Hole Plate	120034G	1155	93.3
Top Leg Brace	120701	716	150.4
Center Brace Tube	120041	331	325.4
Brace Tab	120039	767	140.4
1202			
Hole Plate	120035F	549	196.2
	TOTAL	13458	***8.0***

Table 9-6: Minimum Tka Time For Cell #1

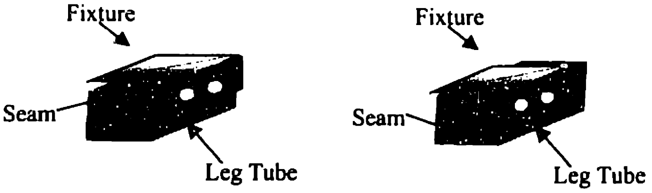
From Chapter 4 (Balanced Production), we saw that Plant L is running all cells at a cycle time very close to that of the customer demand takt time. Notice that the takt time of cells at VRA (8 minutes) is much lower than the takt time of the assembly cell (2.45 hours). The difference in this system versus the one implemented at Plant L is that VRA is machining 18 different part numbers in this one cell. VRA can not afford to have one cell dedicated to each product and it will not be efficient to do so because there will be a lot of extra capacity. In addition to this, VRA does not have only one customer buying 9100 or 1200 series; they have as many as 80 different customers. In this case of low volume/high mix environment, it is impossible to setup the one cell-one customer relationship like Plant L did. Above all, the workers at VRA are still separated from the machine.

Performing single piece continuous flow and the capability to machine 18 different part types in one cell with only 4-5 machines was achieved through the design of fixtures. At VRA, the complexity was built into the fixtures to increase flexibility, decrease changeover time and maximize worker separation from machine. The fixtures at VRA were designed in such a manner that instead of having the fixture attached to the machine, the fixture moves with the part and the operator from machine to machine. Most of the time the part could be machined from start to finish and moved from machine to machine without having to remove the part from the fixture. To achieve this condition, the fixtures were designed to be simple, lightweight and with many poka-yokes devices (mistake proof devices). There were no electrical mistake proofing devices designed into the fixtures. Most of the poka-yokes designed into the fixtures used the contact method.

Operations in the machine shop are less than the takt time when produced in a single piece manner. Rough estimates of cycle times for each operation were determined in previous steps and were compared with the minimum Takt Time. For example to machine a leg tube it was observed to take 5.6 minutes, while the minimum takt time is 8 minutes.

9.3.3 Design Cell Elements

Poka-yokes were designed in every fixture to prevent and detect defects. For example in machining a leg tube, the fixture would detect the welded seam if it is positioned in such a manner that it would touch the fixture (Figure 9-25). If the fixture detects the welded seam, the part could not be clamped to the fixture.



With the seam is at the top, the fixture would not tight strongly the leg tube

With the seam at the bottom, the fixture would tight strongly the leg tube

Figure 9-25: Example of fixture designed at VRA

To increase the flexibility of the new system to be designed, the cells for group #1 and group #2 will be placed one next to the other to create two parallel lines. Some parts will cross from one cell as seen from figure 9-26.

It was decided to leave welding, grinding, and leak test in an area separate from machining because of safety concerns and because of the environment needed for the welding process. The final layout to be implemented in the machine shop is shown in the next figure (Figure 9-26).

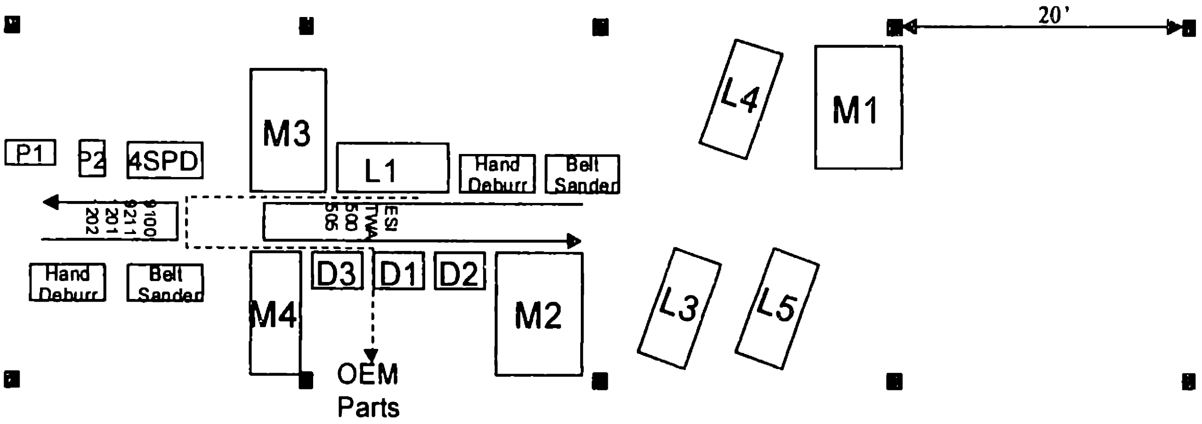


Figure 9-26: Final Layout of Machine Shop at VRA

Since the cells designed in the machine shop are producing eighteen different part types it is neither feasible nor efficient to have standard work-in-process in the cell. In addition to this, using the equation 5.3 the team determined that no SWIP was needed. This makes sense because all operations are manual and continuous, meaning that the worker performs the operations on the machine and then proceeds to the next machine where he conducts the next operation

There is one work loop per part machined in the cells established at VRA. That is, a part is machined from start to finish by one operator. Figure 9-27a shows the path and task/operation time to machine a leg tube for the 9100 series. From figure 9-27b it can be seen that all operations are balanced for the production of a leg tube.

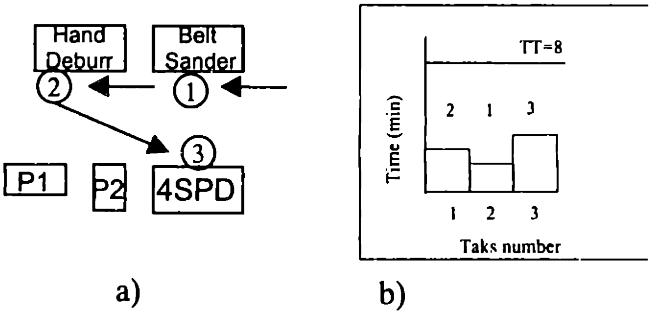


Figure 9-27: Example of a 'work' loop at VRA

9.3.4 Implement New Manufacturing System and Establish Production Team

Once the team and operators agreed on the location of machines and equipment, the company planned a one week shutdown and changes were made during that week. During this week, the changes in assembly were also done and introduction of new equipment and machines for new products.

9.3.5 Develop Operational Activities for New System

Operational Method sheets were developed and posted next to the cell. These sheets were placed in a location where operators could access them easily, although operators are supposed to memorize the standard operations.

All operators in the fabrication area are cross-trained within departments in the fabrication area only. That is, operators working in assembly are not allowed to work on machining and vice-versa but they can work between machine shop, grinding, welding or any other area within the fabrication department. The workforce at VRA is non-technical and most of them do not have any previous experience in machining. This means that more barriers need to be destroyed when training the operators to use different machines. Since many different products can be made in a cell, the operators were measured on how many products they are qualified to produce.

Operators have been certified to do their own inspection. There is no more first and last inspection done by the Inspector. The operator now has full empowerment to perform all necessary judgment and if in doubt he can consult the Inspector.

Just like assembly, production is leveled on a weekly basis. Every Friday, the production for the following week is frozen to level and schedule accordingly. There are at least 18 different part types machined in a cell. However, the time to produce those parts within the cells does not vary much. For this reason, leveling according to time is not necessary.

The two types of customers in the machine shop, are assembly and welding. A pull system was implemented to control the quantity of materials between the assembly and machining to let the machine shop know when to start production. This was done only for the parts going directly to assembly only.

A kanban system between the machine shop and the welding area was done for parts that are consider to be high volume and common, like the stud plate, baffle plate, notch plate and brace tab. A kanban system was not implemented between welding and machine shop for other parts because the team wanted to consider the welding shop as an integral part of machining. The production control person schedules the production of parts going through the machine/welding shop. The scheduling of parts through the shop is based on the consumption of the leg weldments that were placed in a pull system in front of assembly (Figure 9-18).

The parts placed in a kanban system between machine shop and welding were not only high volume parts but also parts that are common among several products. It was decided to calculate the number of kanbans using a pre-determined economic order quantity because of the way these parts were produced. Table 9-7 shows the number of kanbans placed between welding and machining and the type of parts on the kanban system.

Calculating the number of Kanbans using a pre-determined economic lot size

# of Kanbans =	(economic lot size)+(daily demand*safety coe
	Container Capacity

Part Number	Description	Lot Size	Container Cap.	# of Kanbans	# Kanbans
120908	9100 & 1200 Stud Plate	100	50	3	2.2
130069-01	9100 Guard Rail Tube	50	50	2	1.1
130055-01	9100 Support Plate	50	50	2	1.1
120873-01	1200 Baffle Plate	50	50	2	1.1
120034G-02	1200 Hole Plate	50	50	2	1.1
120039B-02	1200 Brace Tab	25	25	2	1.2

Table 9-7: Kanban System implemented between the machine shop and welding area

Parts going directly to assembly were placed on a pull system. For most of the parts, the calculated number of kanbans is three. There are 29 different part numbers implemented in this kanban system. The next figure represents a schematic of the kanban system between assembly and machining:

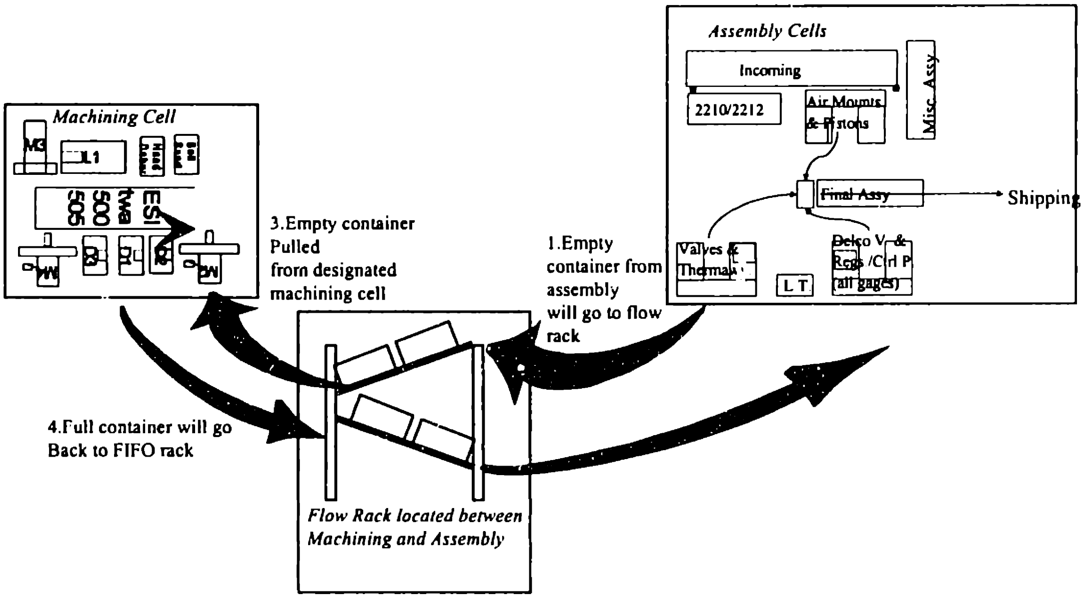


Figure 9-28: Schematic of how the kanban system works between assembly and machine shop

When improving the assembly area, we found that there is no demand interval set from the customer (section 9.2.7). The demand interval in assembly was predetermined to be one week to increase competitiveness in the market and ensure customer satisfaction for the standard products (hot sellers). For this reasons, it was decided to developed the pull interval between assembly and machining and between machining and welding to be less than one week (at least half a week or 2.5 days). Since the replenishment time of parts in the machining and welding is less than one week, there is no need to place any strategic kanban

9.4 Result from Improvements performed at VRA

Some of the results achieved were an On-time delivery of 80% (average) 5 months after the changes were implemented. Figure 9-29 demonstrates how the on time delivery percentage increased over time after the changes were implemented at VRA.

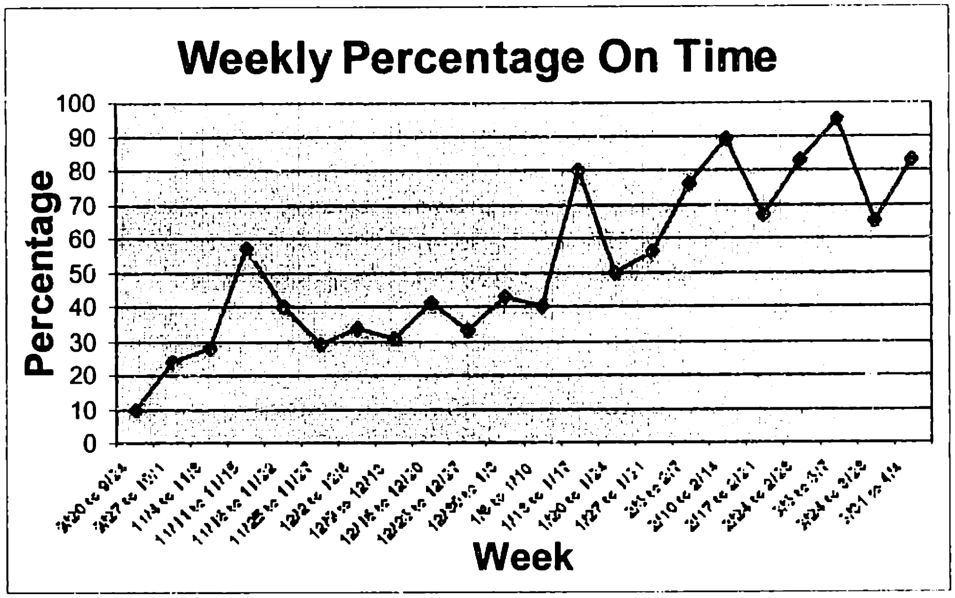


Figure 9-29: On time delivery improvements achieved at VRA

Some of the results in the assembly area (sub-assembly and finals assembly) are as follows:

Vibration Isolation Assembly Area

	Before	After
Time	50 % of the time to finish a unit spent looking for parts	Since point of use stocking no time spent looking for parts. In addition processing time was reduced 15%. Overall 65% reduction in lead time. Output now based on demand for tables and legs
Inventory	1000 ft^2 stock room	Stock Room Eliminated

Optical Table Production

	Before	After
Lead Time	6-8 week lead time on standard products. 10-12 week lead time on specials.	5 days on standard products 2 weeks on specials Has been as little as 3 days
Delivery	0-20% on time delivery	80-90% and still improving
Inventory	WIP: 8-10 Tables	3 Tables
Transportation	> 1500 ft	200 ft

The changes made at VRA created an environment of continuous improvement. Currently operators try to identify ways to make the products in a more efficient way. Incentive programs have not been created yet but the company is studying different possible programs to be implemented. The management-worker relationship is completely different. The greatest improvement of all is the change of management's mentality. Management at VRA always focused on product technology and manufacturing technlogy but never realized that the core of any manufacturing company is the people. The President at VRA now thinks that to be competitive in its market, requires renewed focus on production efficiency along with a higher regard for the people that create the product.

10 Conclusions and Future Work

The hypothesis that a set of lean production system design attributes applies to both the automotive industry and other lower volume industries was proven in this thesis. Two automotive companies, one fashioned in a traditional 'mass' production environment (Plant M), the other designed to meet the customer demand cycle time (Plant L), were analyzed and compared to determined the benefits of a production system that supports lean attributes. From this comparison, it was found that the 'lean' plant (Plant L) achieved higher gains in inventory reduction, lower lead times, lower defects and higher worker satisfaction in assembly and machining (Figure 10-1 and 10-2). The system design at Plant L was compared against the Production System Design Decomposition [Cochran et al., 1998] to better understand the applicability and functionality of many lean production design attributes.

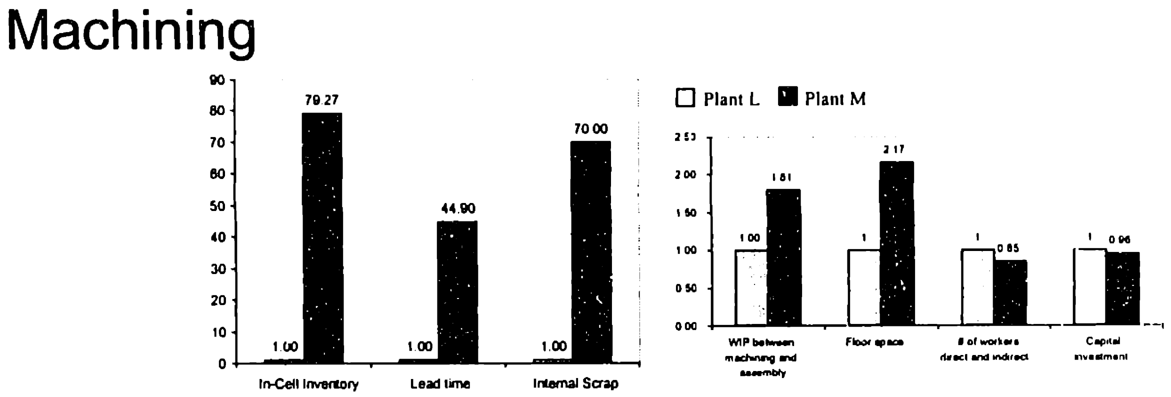


Figure 10-1: Plant L ('lean" plant) and Plant M ('mass' plant) Rack Bar Machining Comparison

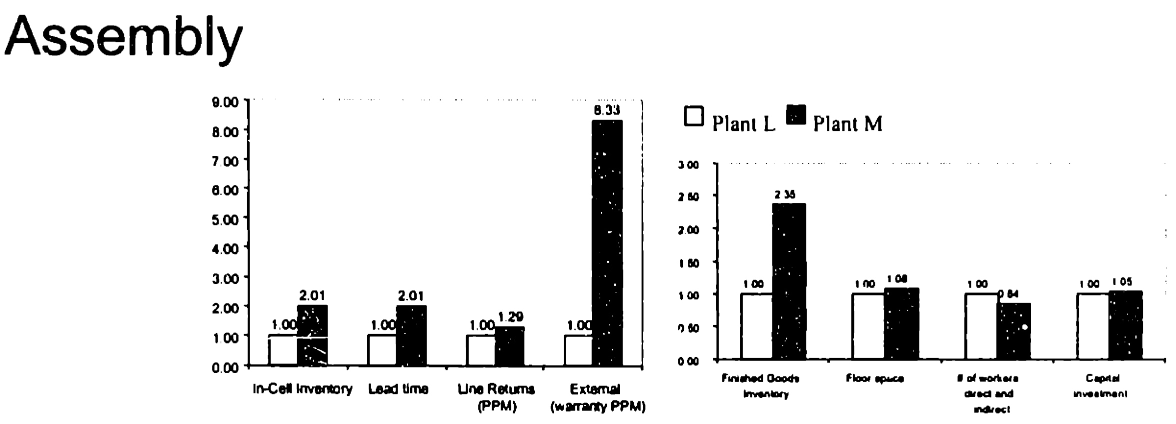


Figure 10-2: Plant L ('lean" plant) and Plant M ('mass' plant) Steering Gear Assembly Comparison

To determined whether the design attributes could be applicable to the companies with lower volumes and more 'complex' products, three companies from the Lean Aerospace Initiative (LAI) engine sector (A, B, and C) were studied and compared against the design attributes. It was found that the only company with a very predictable output (Company C), applied many design attributes that were implemented at Plant L.

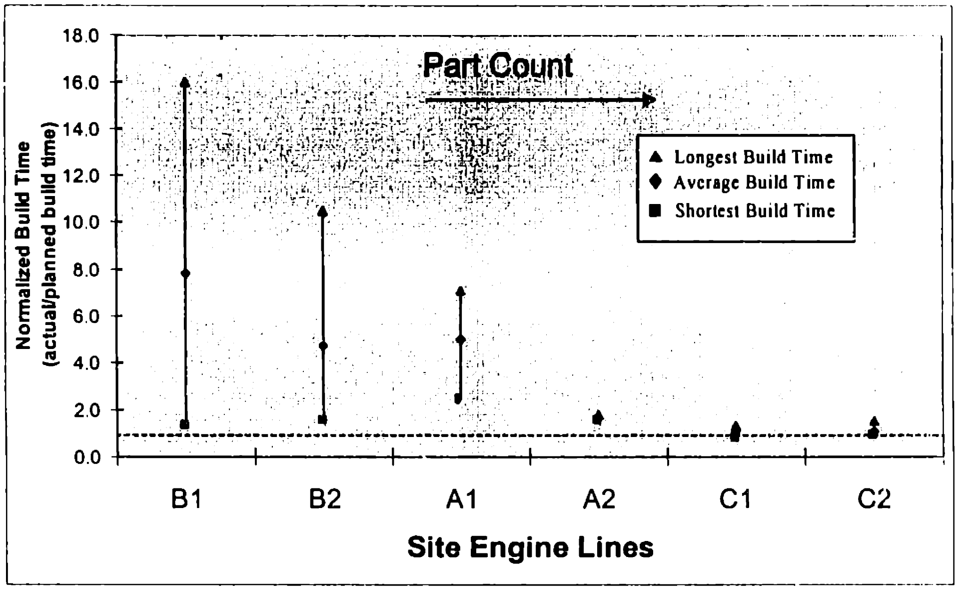


Figure 10-3: Build Time Variability from Three Aircraft Engine Companies

Once the design attributes were compared in different industries and understood, a methodology for implementing the design attributes was developed in Chapter 8. The "lean implementation methodology" can be used to design new production systems or convert existing ones to production systems that espouse the lean design concepts presented in Chapters 4 through 7. The implementation methodology demonstrates that the production system conversion must be supported by the integration of the supply chain and product development. The methodology was applied to convert a make-to-order manufacturing company that is considered to be in the low volume/high mix category. By converting the existing production system and using the lean implementation methodology, the company achieved greater gains in inventory reduction, floor space reduction, higher productivity, better quality and increased on-time delivery.

From the findings presented in this thesis and from the lean implementation methodology, it needs to be reemphasized that economies of time is the new focus of manufacturing rather than just economies of scale. This means that the customer demand cycle time or takt time drives the design of machines and operations that support the requirements of the System and its users.

Future work is needed to determine whether some of the design attributes presented in this thesis can be applied to other sectors in the aircraft industry particularly airframe, electronics and space sector. It is necessary to understand the requirements of every sector and determine whether the same Production Design Decomposition [Cochran, et al., 1998] and its design parameters can be used to design any production system.

Appendix A: Standard Work Routine Sheet

Creating a Standard Work Routine Sheet

Steps:

1. PART NUMBER/PART NAME: Enter part number and name
2. PROCESS: Enter Process (line or cell) name
3. OPERATOR #: There should be on standard work routine sheet for each operator.
4. CUSTOMER DEMAND: Enter per day (or per shift) production required
5. TAKT TIME: Enter takt time
6. DATE PREPARED: Enter date of sheet preparation or revision
7. DEPARTMENT: Enter organizational unit or the department of the process
8. STEP NO: Fill in numbers indicating the sequence in which the operator carries out operations.
9. DESCRIPTION OF WORK: Enter, as detailed as possible, the actual tasks performed by the operator.
10. TIME:

    MAN – Manual work time. Enter the time for operator tasks

    AUTO – Machine time. Enter the time for machine tasks

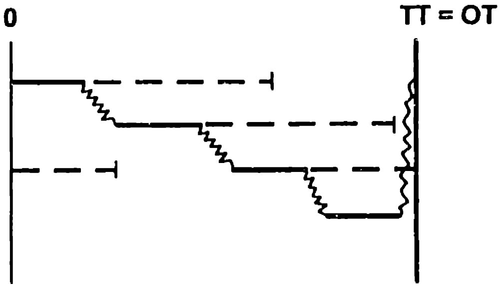
    WALK – Walking time. Enter the time it takes to move to the next station (if any). Approximate 2 feet per second.
11. TIME GRAPH:
    - Indicate Manual Work time with a solid horizontal line
    - Indicate Machine time by a dashed line. If the machine time line intersects the takt time line, break the line and restart the remaining segment at zero.

- Indicate walking time by a wavy line between steps
- Indicate waiting time by a double line
- Indicate takt time with a vertical red line

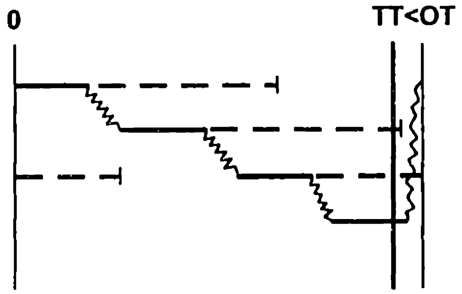
Tips for filling out a standard work routine sheet [Gelderman, 1996]

I. Returning to Start

A. When Operator Cycle Time = Takt Time.

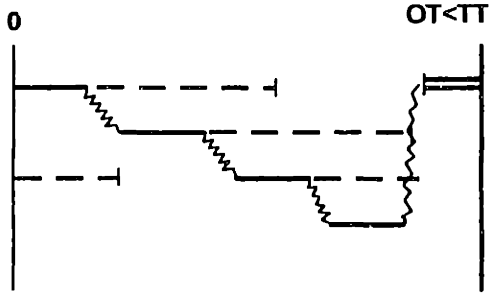


B. When Operator Cycle Time is > Takt Time. Note: This is not a workable situation because customer demand will not be satisfied.

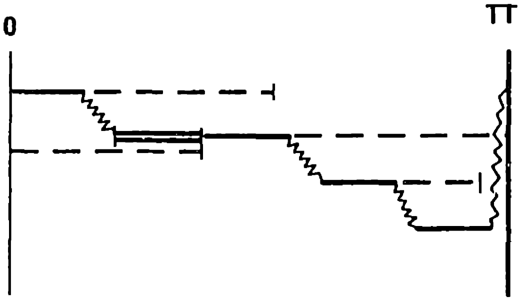


II. Waiting Time.

A. When Operator Cycle Time < Takt Time. Waiting or overproductior occurs.



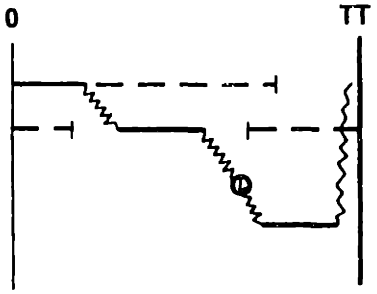
B. When Auto Cycle Time of any machine>Operator Cycle time.



III. Tasks Performed while Walking.

A. Operator Activates a Switch while walking between processes.

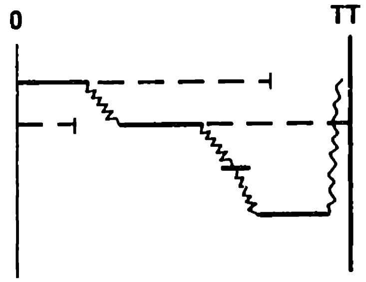
Indicate by adding a Circle over the Walk Line.



B. Operator Assembles while walking between processes.

Indicate by adding a Solid Line thru the Walk Line.

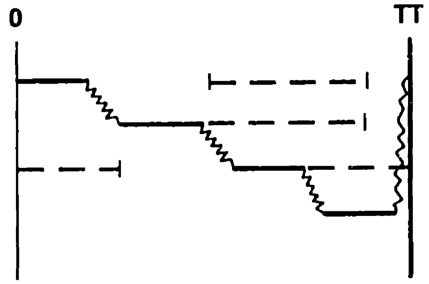
Record the smaller of the times, Walk time or Assembly Manual Time in brackets and do not add to Operator Cycle Time. Add only the larger time because they are performed in parallel by the operator.



IV. Synchronized Starts

A. Two or more machines started by the same switch.

Draw Parallel Dotted Lines starting at the point where the switch is activated.

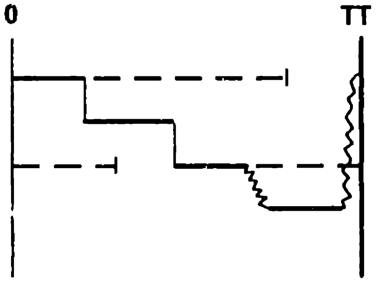


V. Operations Performed at the Same Location.

A. An Operator performs Multiple Tasks without walking.

Break down the Manual Tasks in as much detail as possible.

Show each Task as Steps with Zero walking time.



PART:		DATE:	CUSTOMER DEMAND:
PROCESS:	OPERATOR #: of	DEPT:	TAKT TIME:

#	DESCRIPTION OF WORK ELEMENT	TIME			TIME GRAPH ( )
		MAN	WALK	AUTO	10 20 30 40 50 60 70 80 90
	TOTALS				
	OPERATOR CYCLE TIME				

Appendix B: Glossary

Adapted from the Design and Control of Manufacturing Systems (2.812) Course Taxonomy.

Autonomation: Means the autonomous check of abnormalities in a process. An automatic stopping device is attached to the machine. The worker selects an appropriate solution and executes it.

Balanced Production: All operations or cells produce at the same cycle time. In a balanced system, the cell cycle time is less than takt time.

Capacity: the highest sustainable output rate that can be achieved with the current product specifications, product mix, workforce, contractual agreements, maintenance strategies, facilities and tooling, etc. (e.g. Maximum number of units/year).

Cell: A cell groups together operations according to the product flow. Each cell produces a family of products and is designed to meet the needs of its customer. In manual cells the interface between the machines and the worker loop is critical.

Customer: Receiver of a product. This can be a person, an organization or the subsequent operation within a system (internal and external customer).

Decoupler: A single piece of in-process inventory (WIP) that is intentionally placed between two machines or stations. One function of the decoupler is to uncouple the variation of time and motion between two operations.

Delay – Lot Delay: Occurs when one part in a lot waits on every other part of the lot.

Delay – Process Delay: Occurs when an entire lot is waiting to be processed (queue of orders).

Delay – Run Size Delay: Occurs as a result of the size (quantity) of a production run. The larger the production run quantity:

- the longer the time to produce the order
- the longer the time to produce another product as output
- the larger the Work In Process becomes in the system

Delay – Transport Delay: All factors involved in transportation including waiting for transportation device.

Demand Interval: This is how often the subsequent process picks a standard container. The subsequent process can be external (customer) or internal (next operation). The time is correlated to how long it takes the subsequent process to consume a standard container quantity.

Flexibility: The ability of a manufacturing system to respond quickly, in terms of range and time, to external and internal changes.

Flexibility – Volume: The ability of a manufacturing system to cost effectively vary its output within a given time interval.

Group Technology: A system of algorithms for grouping machines used on sets of common parts. Group Technology was developed in the 1970s. While not developed for Lean Manufacturing, Group Technology can be helpful for a first cut at separating functionally grouped machined into cells.

Heijunka Box: A level scheduling tool that is loaded with Type "A" and Type "B" Kanban cards. The Heijunka box controls the pace of demand placed the production system.

Jidoka: Autonomation

Just-in-Time (JIT): Manufacturing method where downstream operations pull required parts needed from upstream operations at the required time. This process is paced by customer demands. The implementation of JIT requires almost all features of lean manufacturing.

Kaizen: Continuous overall improvement effort. Kaizen has a focus on one problem, which may be eliminated by small incremental improvements.

Kanban: Kanban means card. The Kanban contains information about the product, the quantity to be made, the "supplier" and the "customer", etc. Distinguish between different kinds of Kanban: Production Ordering Kanban, Withdrawal Kanban.

Leveled Production: All operations make the quantity and mix of products demanded by the final customer within a given time (demand) interval. The production run size is greater than one unit, but equal to the quantity pulled by customer during the demand interval.

Machine: A semi-automated or fully automated station, which performs one or more operations.

Machine – single cycle automatic machine: The machine automatically stops after one part is made.

Man – Machine Separation: The worker is not bound to the machine. E.g. the worker is not watching the machine but performing another task, while the machine is processing.

Manufacturing System: The series of operations performed upon material to convert it from raw material or a semi-finished state to a state of further and/or final completion (see also operations).

Mixed Model Production: Mixed model production means the production of different products every day referring to the daily demand. Mixed model production avoids the accumulation of demand over several time periods.

Multi Functional Worker: A worker, who is able to handle different machines and operations. Operating a cell definitely requires this kind of skilled worker.

Multi Machine Handling: One worker operates several machines. The worker is separated from the machine performing another task, while the machine is processing.

One Piece Flow: Producing one unit at a time, as opposed to producing in large lots.

Operations: A specific work element required in the production of a product. All processes can be divided into four basic operations (see Shingo, 1989, pp.5)

- Processing
- Inspection
- Transport
- Storage

Poka-Yoke: Device, which prevents defects from being made.

Production System: The entire collection of functions required to design, to produce, to distribute, and to service a manufactured good. The Production System may include more than one company (e.g. an automaker, its component suppliers and dealers). The production system supports the manufacturing system.

Pull-System: Information system in which the information is flowing the opposite direction of the material flow. In that way material is "pulled" from downstream processes. "Daisy chain" manufacturing technique that allows material to flow in logical sequence, being "pulled" from one process to another as opposed to being "pushed" from order entry. The goal of the pull system is to eliminate speculative production and to provide the ability to produce to actual demand.

Type "A" Pull System: Type "A" Kanban signals to produce product from upstream cell or machine. Possible with repetitively produced products & limited variety. Standard WIP of each product type between each cell/machine.

Type "B" Pull System: Type "B" Kanban signals to produce product from upstream cell or machine. Product type information goes to first cell/machine. Possible with low volume, high variety systems.

Push-System: Information system in which information is flowing in the same direction as the material. In that way the next operation receives materials and production requirements according to a plan. Thus, the material is "pushed" through the system.

Rate - Demand Rate: The rate at which customers demand products (e.g. demand of 100 parts per week.)

Rate – Production Rate: The output of a machine or manufacturing sub-system per unit time (e.g. parts/hour). Analogous to frequency.

Size – Lot Size: Number or quantity of parts moved between operations.

Size – Run Size: For discrete products, the batch is the number of units made in one setup. One batch can consist of several lots, which are transported to the next operation.

Standard Operations: Clearly defined operations and standardized steps for both, the workers and machines.

Standard Work-In-Process: **(SWIP)** A constant amount of WIP that is designed into cellular manufacturing sub-systems. SWIP uncouples variation and establishes a set-point inventory level between operations (see decoupler).

Station: A physical location and required facilities and tools at which one or more operations are performed.

Sub-System or Cell: A collection of machines and stations required to perform a specified set of operations on a product or group of products. Examples: an engine block machining transfer line; a vehicle assembly line; a Flexible Manufacturing System (FMS) for machining jet engine turbine blades.

Synchronized Production: All operations produce exactly the same sequence of parts demanded by the customer (e.g. same mix, rate, and quantity). The production run size and lot size is truly one unit.

Time – Cycle Time: The time interval between the production of two sequential parts by a machine or sub-system. The production rate is the inverse of the cycle time.

Time – Manufacturing Throughput Time: The time required for a part to pass through the manufacturing system. Measured from the time processing begins on the raw material to the time the processed product exits the final operation.

Time – Order Lead Time: Time interval from order input to shipping of finished good. Order lead time consists of administrative time and throughput time. (See Response Time.)

Time – Processing Time: The time during which material is being changed, whether it is a machining operation or an assembly.

Time – Purchasing Lead Time: The total lead time required to obtain a purchased item. Included here are order preparation and release time; supplier lead-time; transportation time; and receiving, inspection and put-away time.

Time – Replenishment Time: The time it takes the system or sub-system (cell) to replenish a container with a standard quantity of parts.

Time – Response Time: For a Type "A" part this is the time from order receipt to shipping, and does not include replenishment time since a small amount of "A" type parts are kept in standard WIP, or finished goods inventory. For Type "B" parts the response time is equal to the Order Lead Time since replenishment time must be included. Type "B" parts are not kept in finished goods inventory and are made to order only.

Time – Setup Time (or changeover time): The time required to changeover a machine, resource, work center, or line from the last good piece of part type A to the first good piece of part type B. Distinguish internal setup (all activities, which require the machine to be shut) from external setup (activities, which do not require the machine to be shut down).

Time – Standard Time: The length of time that should be required to run one part through an operation by a worker. Standard time assumes an average worker following prescribed methods and allows time for rest to overcome fatigue.

Time – Takt time: Takt time defines customer demand cycle time. It is the quotient of available time per shift (day) to average demand per shift (day).

Time – Throughput Time: refers to the length of time from when material enters a production facility until it exits.

Waste: The Toyota Production System defines seven wastes:

Overproduction means to produce more than demanded or produce it before it is needed. It is visible as storage of material. (it is the result of producing to speculative demand).

Inventory or Work In Process (WIP) is material between operations due to e.g. large lot production or processes with long cycle times. (e.g. EDM at Palmer)

Transportation does not add any value to the product. Instead of improving the transportation it should be minimized or eliminated (e.g. forming cells).

Processing - The waste of processing itself anticipates the question why a specific processing step is needed and why a specific product is produced. All unnecessary processing steps should be eliminated.

Motion - Waste of motion relates to the motion of the workers, machines, and transport; e.g. due to inappropriate location of tools and parts. Do not automate wasted motion, but improve the operation itself.

Waiting - The worker should not wait for the machine. The principle is to maximize the utilization/efficiency of the worker instead of maximizing the utilization of the machines.

Making defective products is pure waste. Prevent the occurrence of defects instead of finding and repairing defects.

Work-In-Process: (WIP) The total inventory existing within a manufacturing system. Does not include raw materials and components prior to the first operation in the system or finished goods after the final operation.

5S: 5S stand for Seiri, Seiton, Seiso, Seiketsu, and Shitsuke, which collectively translate to a cleanup activity at the work place.

Seiri: to clearly separate necessary things from unnecessary ones and abandon the latter.

Seiton: Organize neatly arrange and identify things for ease of use. Everybody must be able to find the needed things quickly. Everything has to be in its determined place.

Seiso: Clean up to always clean up; to maintain tidiness and cleanliness.

Seiketsu: Sustain to have workers maintain the 3S mentioned above (Seiri, Seiton, Seiso).

Shitsuke: Systematic to have workers make a habit of always conforming to rules.

5W's and 1H: (This can also be the 5 Why's) To find the root causes of waste there are 6 questions asked again and again until the answer is found:

Who: subject of production

What: objects of production

When: time

Where: space

Why: find the cause for each of the above because they are all important factors in unraveling a problem

How: methods to solve the problem

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