Application of the Production System Design Framework in the Automotive Components Industry

by

Carlos Tapia

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Signature of author..
Department of Mechanical Engineering
May 5, 2001

Certified by..
David S. Cochran
Assistant Professor of Mechanical Engineering
Thesis Supervisor

Accepted by..
Ain A. Sonin
Chairman, Department Committee on Graduate Students

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ABSTRACT

The environment that companies face nowadays is increasingly competitive. In this setting firms must ensure that its Production System is aligned with its business objectives. However, Production Systems can be extremely complex and their design involves many different disciplines. The Manufacturing System Design Decomposition (MSDD) developed by the Production System Design Laboratory at MIT is useful to identify the objectives (Functional Requirements – FRs), and the corresponding implementation (Design Parameters – DPs) for the key decisions that must be made to design a manufacturing system. This work presents the Production System Design Framework, which is based on the MSDD, as a roadmap to approach the intricate design and implementation process. Special attention is placed on an important part of the framework: The Production System Design and Deployment Steps.

This thesis exhibits the direct application of the PSD Framework to the design and implementation of an automotive components production system. The basis for this design is the MSDD and it is implemented through the Production System Design and Deployment Steps. Each step is described in detail and it is explained how it was adapted to the particular requirements of the project. Additionally, a manufacturing system of electronics components is examined. Two different system designs for the same product are studied. The analysis is performed using traditional performance metrics as the evaluating criteria. In addition, this analysis is contrasted to an analysis made using the MSDD. The similarities of the results validate the importance of the MSDD. Furthermore, the MSDD is used to identify potential areas for improvement.

Thesis Supervisor: David S. Cochran
Title: Assistant Professor of Mechanical Engineering

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Introduction

This thesis has three objectives: to present a structured framework for the design and implementation of manufacturing systems, to present a case study where the framework is utilized and to provide a case study where the validity of the approach is tested.

Manufacturing systems can be extremely complex and their design involves many different disciplines. In order to tackle a problem of this magnitude in a structured manner, the Production System Design Laboratory at MIT developed the Manufacturing System Design Decomposition (MSDD) [Cochran, Arinez, Duda, Linck, 2000]. The MSDD was developed using Axiomatic Design and it is the centerpiece of the framework presented in this work. The MSDD provides the requirements of the system and helps the designer relate objectives and means, and low-level decisions to the higher-level goals of the organization. The MSDD and the design and implementation framework are put to practice in the design of a real Manufacturing System and the analysis of an evolving system respectively.

Chapter Summaries

Chapter 1: The Production System Design Framework

This chapter introduces the Production System Design (PSD) Framework that was developed Production System Design Laboratory at the Massachusetts Institute of Technology under the direction of Professor David S. Cochran. The chapter begins with the description of the Axiomatic Design process. Axiomatic Design is a tool that was developed to provide structure and a scientific foundation to the design process [Suh, 1990]. The Axiomatic Design methodology aids in the process of deciding *what* a design intends to do (Functional Requirements) and *how* it intends to achieve it (Design Parameters) and is provides the structured thought process behind the Manufacturing System Design Decomposition (MSDD).

The chapter briefly describes the components of the PSD framework: the MSDD, the Manufacturing System Design Matrix, the Manufacturing System Design Evaluation Tool, the Equipment Evaluation Tool, the Manufacturing System Design Flowchart and the Production System Design and Deployment Steps.

Chapter 2: The Production System Design and Deployment Steps

This chapter recognizes the complexity in manufacturing systems and the difficulty of identifying a logical path to follow when thinking about the features of a system. To approach this problem, this chapter presents the Production System Design and Deployment Steps shown in Table 1 from the Production System Design and Deployment Framework as a roadmap to approach the intricate process of designing the Production System and its subsequent implementation. Each one of the twelve steps is described in detail throughout the chapter.

Table 1: The Production System Design And Deployment Steps

Step 1.	Create a common mental model of the Manufacturing System Design objectives and means
Step 2.	Develop the Manufacturing System Design Decomposition and align Performance Measures with the FR's
Step 3.	Identify the final (external) customer and create a customer-focused capacity planning process (that enables capacity to be put in place according to a Value Stream and not operations)
Step 4.	Define customer Takt time (subject to < 30 seconds)
Step 5.	Define the linked-cell system flow
Step 6.	Form cells based on takt time
Step 7.	Reduce setup time in final assembly
Step 8.	Level final assembly – reduce the run size
Step 9.	Operate the linked system with leveling and pacing (Initially with large SWIP 'Standard Work in Process' between cells)
Step 10.	Systematically reduce SWIP between cells to reduce variation – improve reliability of machines, operator's work, improve capability of machines & mistake-proof processes.
Step 11.	Link Suppliers
Step 12.	Align product development with the linked-cell system of plants

Chapter 3: Visteon Axle Plant: Designing the Production System for the Rainbow Product

This chapter covers the work performed by the author in the design of a manufacturing system at a Visteon Axle Plant. The system is intended to produce a single differential (named the Rainbow differential) with no product variations. The basis for this design is the MSDD and it is implemented through the Production System Design and Deployment Steps. The chapter follows each step and describes how it was adapted to the particular requirements of the production of the Rainbow differential.

Chapter 4: Case Study: Visteon Electronics Plant

This chapter presents the work carried out at Visteon North Penn Electronics Plant, a manufacturer of electronic engine controllers for automobiles. The production process in this plant is of particular interest for the scope of this thesis because two different production approaches are used during one stage of the production of these modules. These approaches are the typical asynchronous transfer line and a cellular approach. The chapter explains the material and information flow throughout the plant. It then presents an analysis the two different production approaches that are used. The analysis is performed using traditional performance metrics as the evaluating criteria. Additionally this analysis is contrasted to an analysis made using the MSDD. The similarities of the results validate the importance of the MSDD. Furthermore, the MSDD is capable of identifying potential areas for improvement. Finally, the equipment at North Penn is evaluated through the lens of the MSDD.

Chapter 1: The Production System Design Framework

1.1 Axiomatic Design

Axiomatic Design is a tool that was developed to give structure to the design process. Traditionally, design has not been considered a scientific process but rather a skill that is innate to some, and that cannot be developed [Chu and Cochran, 2000]. The fundamental goal of Axiomatic Design is to create a science base for design and a theoretical foundation based on a systematic thought process that can be applied in any design scenario [Suh, 1990]. There are many elements in the design process, but the axiomatic design process focuses on the generation of requirements and the corresponding means to achieve them.

Axiomatic Design answers the basic questions concerning *what* the design intends to achieve and *how* it intends to achieve it [Suh, 1990]. It characterizes the design into three domains: the Customer Domain, the Functional Domain and the Physical Domain. In order to achieve the initial objectives, a continuous interaction between these three domains is necessary. Figure 1-1 illustrates the design domains and the interactions between them. The customer domain relates to the customer related objectives such as customer needs, expectations, specifications, constraints, etc. The first step in the axiomatic design methodology begins in this domain with the identification of customer needs. The customer domain leads to the development of Functional Requirements (FRs) that capture the answer to the first question: "*what* the design intends to achieve?" The Design Parameters (DPs) answer the second question concerning how to achieve the requirements. Regularly, it is necessary to further decompose the DPs into lower level FRs in order to identify what is needed to realize the DP in question. This process is repeated for the new set of FRs until the level of detail is enough to complete the design.

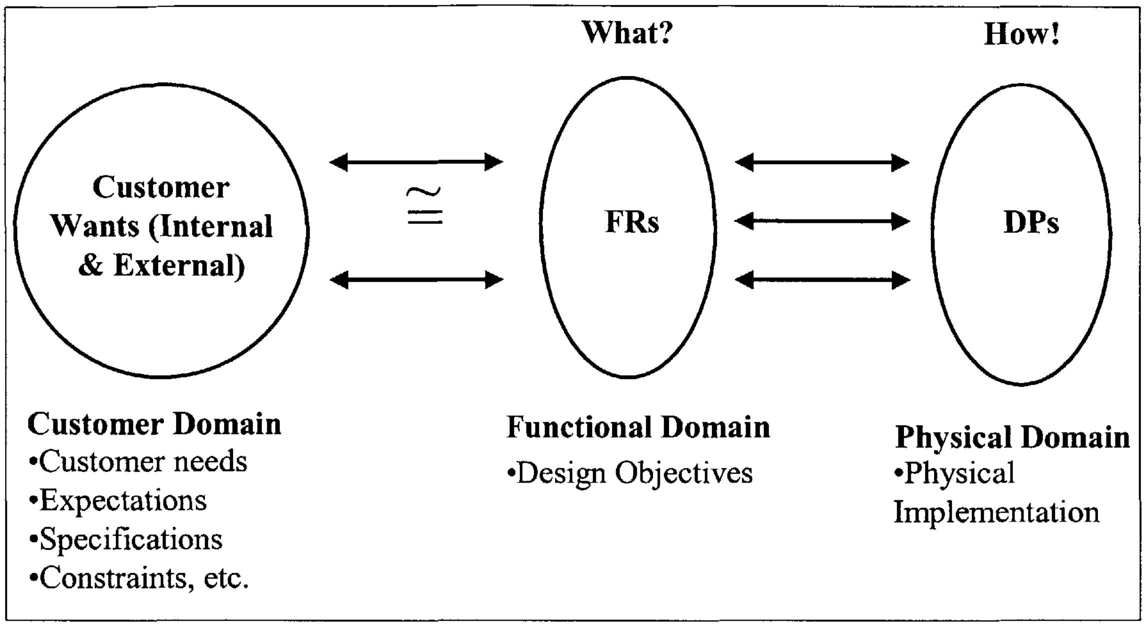


Figure 1-1: The Axiomatic Design Domains [Suh, 1990]

In Axiomatic Design, two axioms are used to ensure the selection of the best set of possible DPs [Suh, 1990]:

1. *The Independence Axiom:* Maintain the independence of the functional requirements.

2. *2. The Information Axiom: Minimize the information content of the design.*

The independence axiom states that the optimal design solution includes FRs that can be individually satisfied without affecting the rest of the FRs. The relationship between FRs and DPs can be represented with design matrices as follows:

$$\{FR's\} = [A]\{DP's\} \qquad (1)$$

where the relationships between the vector of FRs and the DPs is represented with the design matrix A [Tate, 1999]. The design matrix A contains either a 0 or an X to indicate the presence or absence of a relationship between an FR and the corresponding DP. If the adjustment of a DP affects in any way the achievement of an FR, the design matrix uses an X to represent this relationship. Equation 2 shows an example of such representation:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (2)$$

The information contained in the design matrix can also be displayed graphically. The relationships marked with an X in the off-diagonal elements of the design matrix are replaced with arrows that start at the DP in question and point to the FR that is affected. Figure 1-2 shows a graphic representation of equation (2).

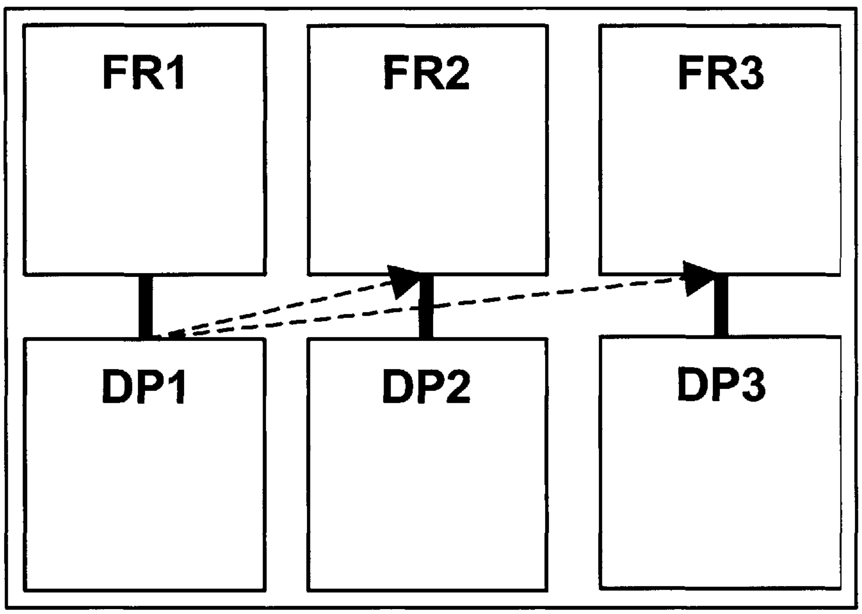


Figure 1-2: Graphical representation of a design matrix

When the first axiom is satisfied, the design matrix will be diagonal. The DPs will only affect their corresponding FRs. The design represented with a diagonal matrix is said to be uncoupled and is the best design. On the other, hand there are cases where the independence axiom cannot be fully satisfied. The most interesting case is where the design is partially coupled and the design matrix can be arranged such that the result is an upper triangular or lower triangular matrix. In this case the design is said to be "decoupled" and is also an acceptable design although its implementation becomes path-dependent. The last case is where the design matrix cannot be arranged into a triangular matrix leading to an unacceptable coupled design.

The second axiom states that an optimal design should minimize the information content. The idea is to minimize the complexity of the design, but it is rather difficult to quantify this parameter. The second axiom was not formally utilized when developing the MSDD and thus will not be discussed further [Cochran, Arinez, Duda and Linck, 2000].

1.2 The Production System Design Framework

In order to discuss the implications of the design of production systems, the concept of system must first be defined. A system takes in a set of inputs and acts on them to produce a desired output [Parnaby, 1979]. A system can be conformed by several subsystems that interact and the overall system's output is the product of these interactions. A Manufacturing System is a subsystem of a Production System. A Manufacturing System consists of the arrangement and operation of machines, tools, material, people and information to produce a value-added physical, informational or service product whose success and cost is characterized by measurable parameters [Cochran, 1999]. A Production System in turn is comprised of the Manufacturing System as well as all the functions that support its functioning.

The inherent complexity of a Production System makes its design a challenging task. In many cases, the complexity of such a system drives the optimization of subsystems in the hope that the sum of these individual pieces will result in the best overall system design. A good Production System design is seldom achieved through this approach resulting in system that are difficult to control and do not meet the enterprise's objectives.

The Production System Design (PSD) Framework developed in the Production System Design Laboratory at the Massachusetts Institute of Technology provides a methodology to convert the objectives of the organization into design and implementation actions on the shop floor [Cochran, 1999]. It utilizes Axiomatic Design to recognize the objectives (Functional Requirements) and the corresponding physical implementation (Design Parameters). The PSD Framework also serves as a platform to effectively communicate the goals and decisions to the people that form the organization. Furthermore, it goes beyond the design stages and aids in the implementation and control of the Production System.

The Production System Design Framework consists of the following components:

- The Manufacturing System Design Decomposition (MSDD)
- The Manufacturing System Design Matrix
- The Manufacturing System Design Evaluation Tool
- The Equipment Evaluation Tool
- The Manufacturing System Design Flowchart, and
- The Production System Design and Deployment Steps.

Figure 1-3 shows the PSD Framework with all its components.

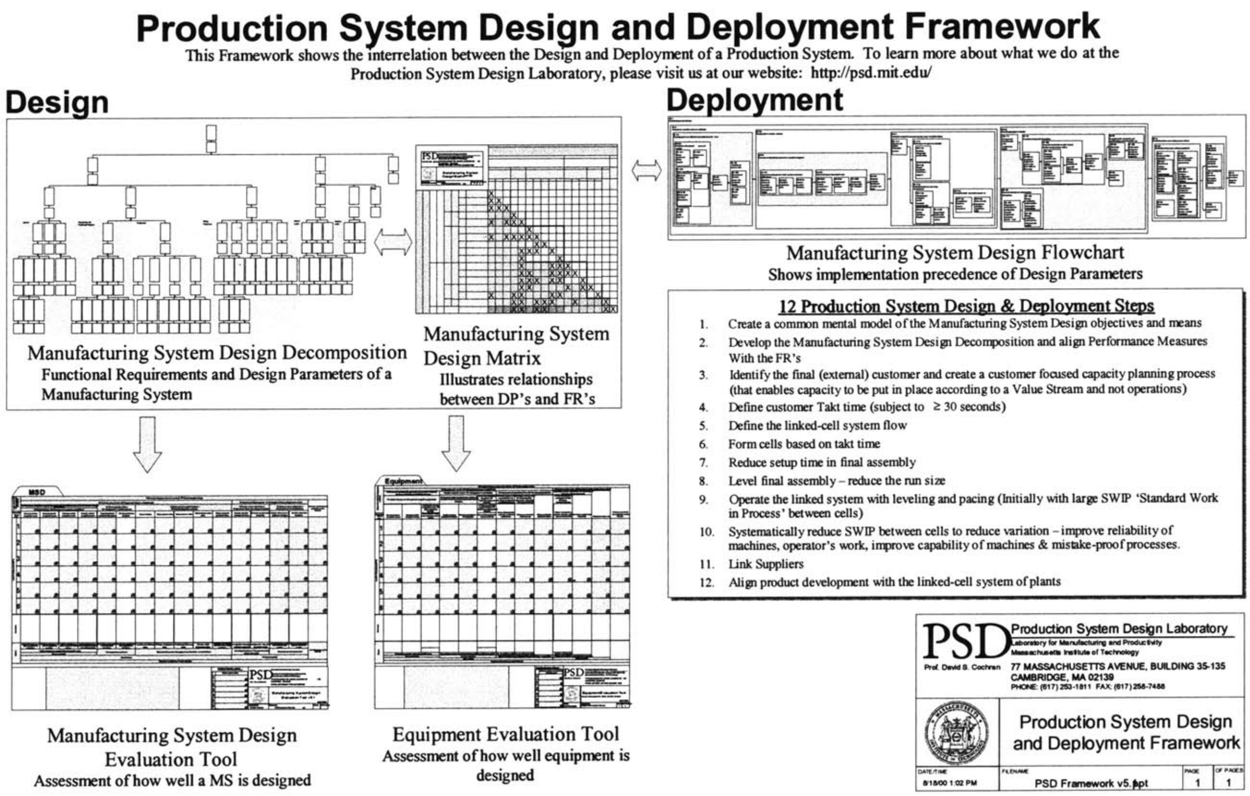


Figure 1-3: The Production System Design and Deployment Framework

The MSDD is the focal element of the PSD Framework. It identifies the objectives of the system design as well as the means to achieve those objectives. Because of its importance, it will be described in more detail in the next section.

The Manufacturing System Design Matrix is the direct representation of the relationships between the Functional Requirements and Design Parameters at the fourth level of the MSDD. It clearly communicates the path dependencies in the design and identifies the order in which the objectives must be satisfied. It also demonstrates that the independence axiom of Axiomatic Design is satisfied.

The Manufacturing System Design Evaluation Tool and the Equipment Evaluation Tool where derived also from the MSDD. The tools evaluate the extent to which a particular manufacturing design achieves the FRs stated in the fourth level of the MSDD [Gomez, 2000]. The tools allow the designer to use a six level grading system to evaluate different aspects of the design. Both evaluation tools follow the same format but the Equipment Evaluation Tool focuses on the equipment subsystem of a Manufacturing System.

The Manufacturing System Design Flowchart is a graphical representation of the system design architecture [Suh, Cochran, Lima, 1998]. The flowchart is directly derived from the design matrix. It represents the path-dependent design information shown in the design matrix. The implementation precedence is graphically displayed in a clear fashion to facilitate its communication.

Finally, the Production System Design and Deployment Steps provide a roadmap to approach the intricate process of designing the Production System and its subsequent implementation. This thesis will focus on this component of the PSD Framework. Chapter 2 describes in detail each step and discusses its role and importance in the design and deployment process.

1.2.1 The Manufacturing System Design Decomposition

The Manufacturing System Design Decomposition (MSDD) is the centerpiece of the Production System Design framework. It identifies the design relationships to achieve an optimal production system design [Cochran, 1999]. The MSDD is the direct result of applying Axiomatic Design concepts to the design of a Manufacturing System. Axiomatic Design is useful to identify the objectives (Functional Requirements – FRs) and the corresponding implementation (Design Parameters – DPs) for the key decisions that must be made to design a manufacturing system. The focus of the MSDD is on those decisions and activities that will be under the direct control of the group of engineers, managers and operators involved in the design and control of the manufacturing system.

The Decomposition starts with an overall objective (FR) of improving ROI over the life of the system in question [Cochran, Arinez, Duda, and Linck, 2000]. The Design Parameter chosen to satisfy the initial FR is: "Manufacturing System Design." The DP was chosen over several other possible ways of improving ROI because the focus of the MSDD is on the design of manufacturing systems. The DP is still vague and further decomposition is needed to reach a comprehensive design. The next level of FRs is derived based on the components of ROI:

$$ROI = \frac{REVENUE - COST}{INVESTMENT} \qquad (3)$$

Therefore, the Investment and Cost of the system must be minimized. On the other hand, the Revenue must be maximized. Again, these elements are considered over the life of the manufacturing system in order to maximize the long-term return on investment. The process continues with the identification of DPs for these lower-level FRs. This process is repeated where more detail is needed. The decomposition of the initial FRs in this manner leads to lower-level implementable actions that can be grouped into functional areas. Figure 1-4 shows the first few levels of the MSDD and the categorization of the branches into functional areas. Appendix A contains the complete version of the MSDD.

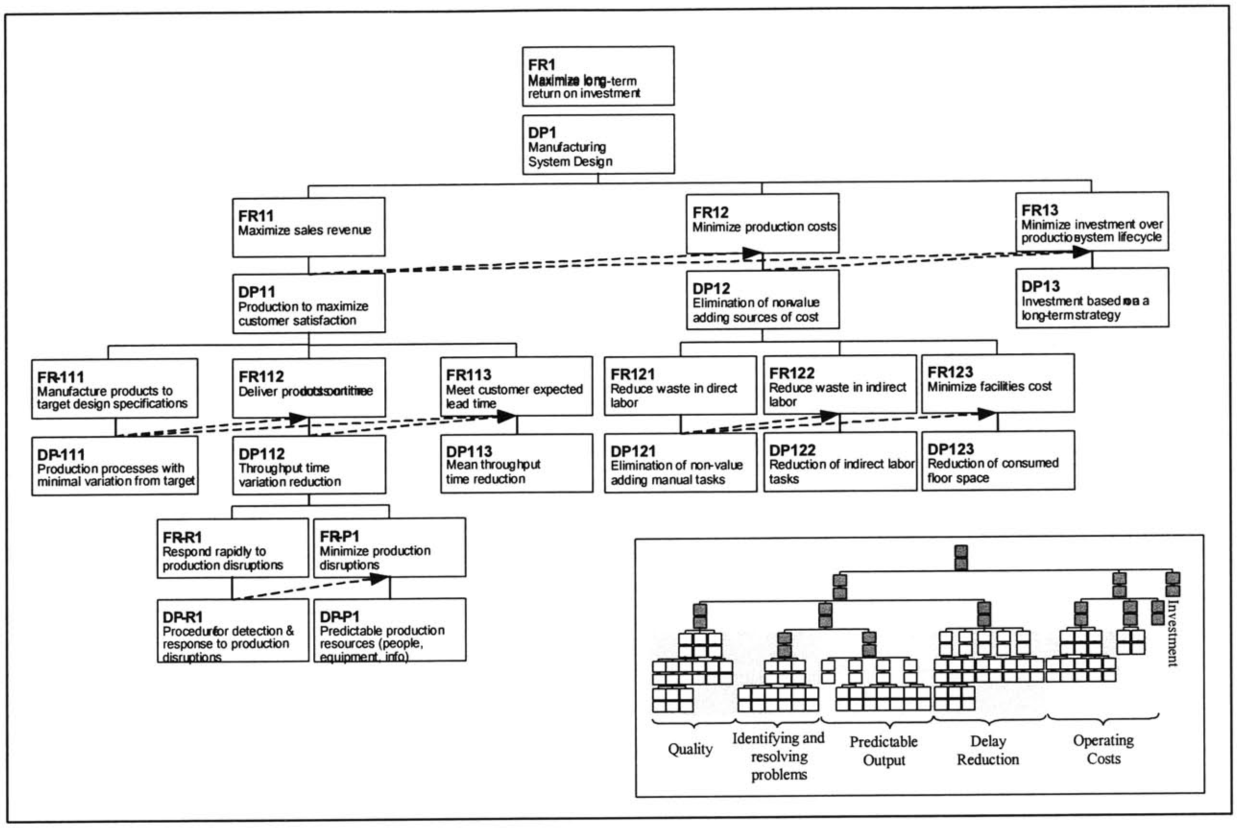


Figure 1-4: Upper levels of the MSDD

Chapter 2: The Production System Design and Deployment Steps

Manufacturing systems can be extremely complex and their design involves many different disciplines such as product development, process design, accounting, scheduling, information systems, equipment design, etc. Complexity makes it difficult to identify a logical path to follow when thinking about the features of a system. Shingo has shown that even proven tools and solutions used by Toyota will fail if the necessary infrastructure is not in place [Shingo, 1981]. The MSDD in itself is a great tool to understand the characteristics that must be present in a manufacturing system and the means to achieve each specific objective, but it does not provide a methodology for structuring the design of those features. Monden on the other hand, developed a guide for the design of a manufacturing system as a set of activities that must be implemented in a particular order. However, his approach does not distinguish objectives and means, which makes his approach difficult to use [Monden, 1998]. Figure 2-1 shows the relationship between these elements.

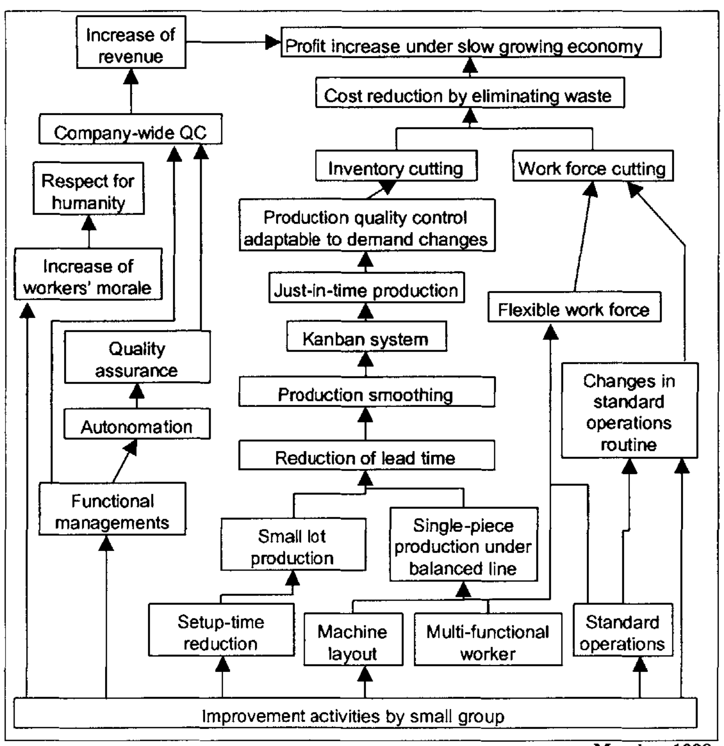


Figure 2-1: Hierarchical approach to production system design

The Production System Design and Deployment Framework, which is based on the MSDD, was developed by the Production System Design Laboratory at MIT to provide a methodology to translate the objectives derived from the MSDD into a comprehensive design and implementation process [Cochran, 1999]. In particular it presents the sequence of twelve design steps shown in Table 2-1. This work studies the twelve design steps as a production system design guideline. The following sections describe each step in more detail. The role and importance of each step is discussed as well as issues related to their application.

Table 2-1: The twelve steps of Production System Design [Cochran, 1999]

Step 1.	Create a common mental model of the Manufacturing System Design objectives and means
Step 2.	Develop the Manufacturing System Design Decomposition and align Performance Measures with the FR's
Step 3.	Identify the final (external) customer and create a customer-focused capacity planning process (that enables capacity to be put in place according to a Value Stream and not operations)
Step 4.	Define customer Takt time (subject to < 30 seconds)
Step 5.	Define the linked-cell system flow
Step 6.	Form cells based on takt time
Step 7.	Reduce setup time in final assembly
Step 8.	Level final assembly – reduce the run size
Step 9.	Operate the linked system with leveling and pacing (Initially with large SWIP 'Standard Work in Process' between cells)
Step 10.	Systematically reduce SWIP between cells to reduce variation – improve reliability of machines, operator's work, improve capability of machines & mistake-proof processes.
Step 11.	Link Suppliers
Step 12.	Align product development with the linked-cell system of plants

2.1 Step 1: Create a common mental model of the Manufacturing System Design objectives and means

It may seem that this step has no direct influence in the physical design of the system as it relates to the mental state of the people involved with the system. It is a reminder that production systems are composed not only of the physical hardware but also include the people involved with it. Although the equipment usually performs most of the material transformation, people are invariably controlling its design and functions. For this reason, it is essential that people at all levels of the organization, from management to direct labor, be aware of the production system's objectives.

2.2 Step 2: Develop the Manufacturing System Design Decomposition and align Performance Measures with the FR's

The performance measurement system of a company is often overlooked when the production system is designed. Proof of this is that many businesses are still measured using the same accounting systems that were developed at the beginning of the century. The conditions at the time where much different form what it is seen today. Nowadays firms experience different energy costs, wages have changed and even environmental restrictions now play an important role.

A company's performance measurement system drives its behavior and thus, affects its ability to achieve its strategic objectives. The role of performance criteria is twofold. First, it provides the firm with a method to compare its position with respect to its competitors and the market, and to identify possible opportunities for improvement. Second, it serves as a monitor to assess whether or not the firm is marching in the right direction towards the achievement of its strategic goals [Wisner and Fawcett, 1991]. In a complex organization it is difficult to effectively communicate the high-level goals of the company to the players at the lower levels. Without an aligned performance measurement system, the employees are driven to behave in a dysfunctional manner in an attempt to improve indicators that do not reflect the company's objectives.

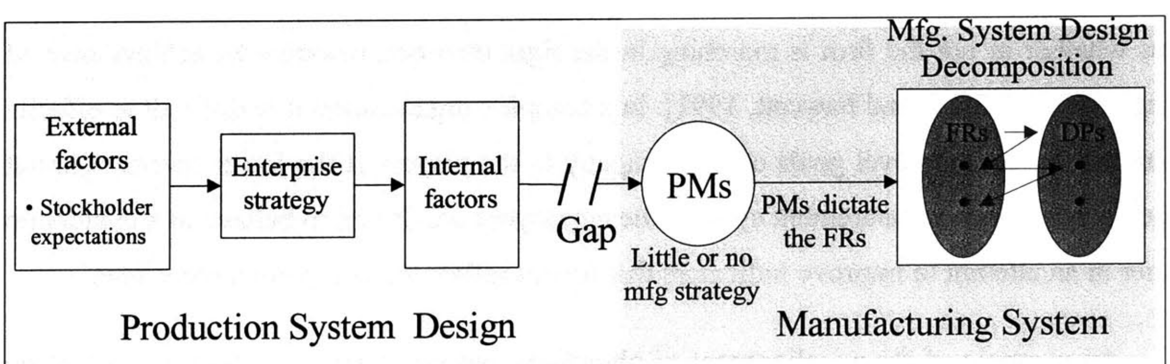
An example of the misalignment of objectives and measures is evident in the traditional manufacturing cost accounting system. In particular, the way that the production unit cost is calculated often leads to misleading information, which in turn serves as the basis for making important business and operational decisions. Let us consider the manner in which unit cost is calculated:

$$UnitCost = \frac{(DirectLabor + Material + OverheadAllocation)}{\text{UnitsProduced}} \qquad (4)$$

where,

$$OverheadAllocation = (DirectLabor \,/\, TotalPlantDirectLabor) * TotalOverhead \qquad (5)$$

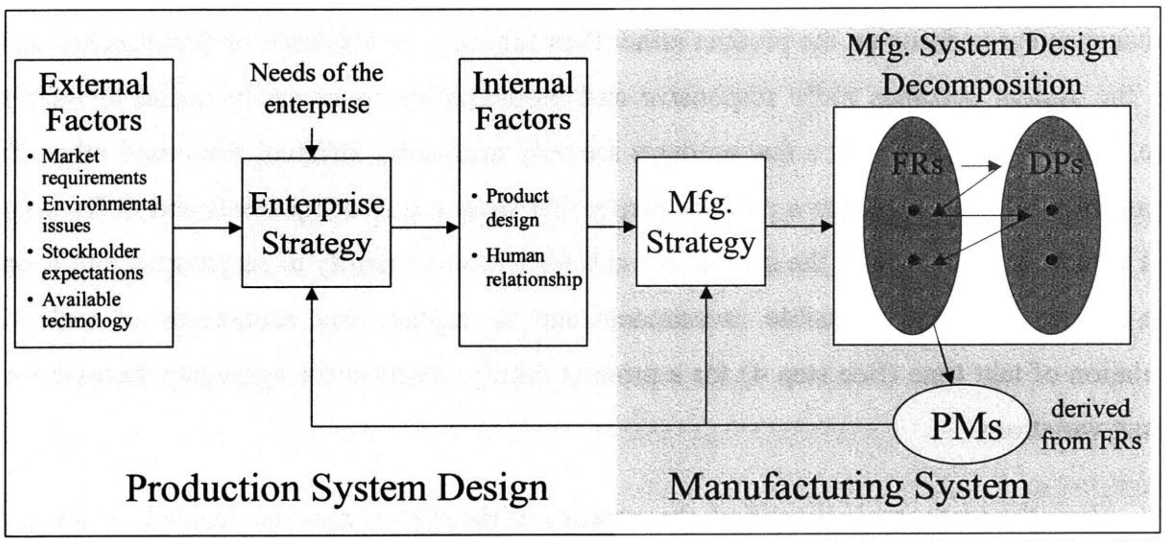
The calculation of unit costs using Equation (1) and Equation (2) places a very heavy weight on the direct labor associated with the production of the part. Furthermore, the allocation of overhead costs based on the portion of direct labor needed to manufacture the part motivates the reduction and ultimately the elimination of direct labor in all processes. This approach results in the selection of highly automated equipment that is more expensive and complex. As a result, these types of machines require more resources to maintain. Additionally, the cost of the equipment stimulates the use of machine utilization as an important performance measure often times at the expense of overproduction. It can be seen that in an environment like this, there is a discontinuity between the enterprise objectives and the performance measurement system and as a result, the measurements drive the objectives in the manufacturing system [Cochran, Kim and Kim, 2000]. Figure 2-2 illustrates how this gap has an effect on the design of the manufacturing system.



Cochran, Kim and Kim, 2000

Figure 2-2: Incomplete Performance Measures Driving Manufacturing System Design

The Manufacturing System Design Decomposition (MSDD) identifies the functional requirements throughout all aspects of the manufacturing system and the means to achieve them. For each of these requirements it presents a corresponding performance measure. This method of developing the measurement system ensures that the behavior of the manufacturing system is in line with the high level objectives of the organization. In this way, employees have the right information regarding what actions improve the state of the system relative to the company's strategy. The diagram in Figure 2-3 illustrates the process in which the performance measures must be derived.



Cochran, Kim and Kim, 2000

Figure 2-3: Performance Measures to Achieve the Goals of the Manufacturing System Design and Production System Design

The complete version of the MSDD along with the performance measures associated with each FR-DP pair can be found in Appendix A.

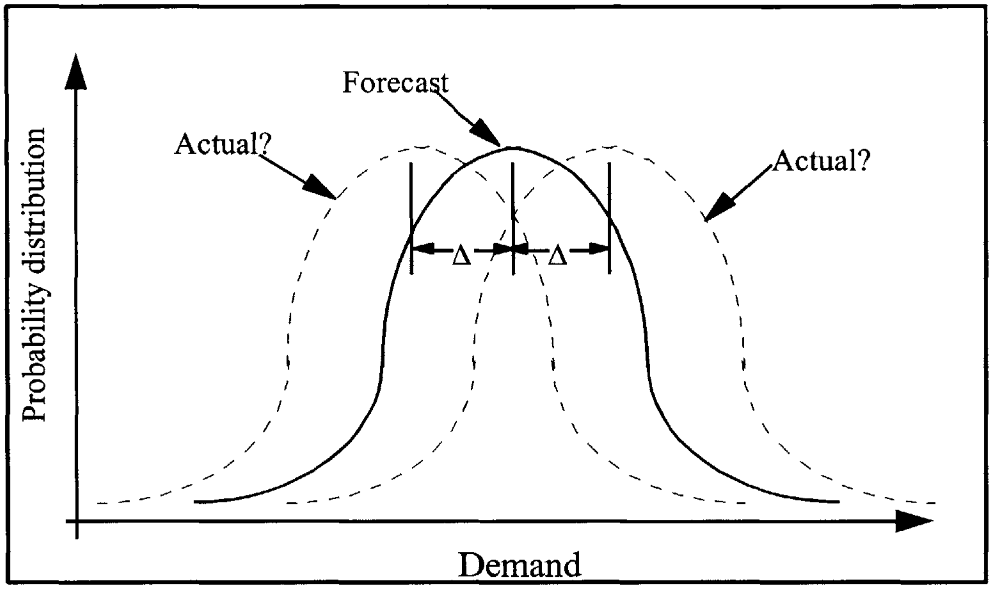
2.3 Step 3: Identify the final (external) customer and create a customer-focused capacity planning process (that enables capacity to be put in place according to a Value Stream and not operations)

The MSDD has as its primary objective to maximize the long term Return on Investment (ROI). There are three ways to achieve this goal that derive directly from the formula to calculate

ROI (See Equation 3): Maximize sales, minimize costs and minimize initial investment. This step is concerned with the maximization of sales. To achieve these goals we must pay attention to the customer. There are several factors that increase sales through attracting new customers but most of the techniques fall outside of the scope of production system design. Nevertheless, the production system plays a key role in retaining existing customers through high quality, reduced lead times and low cost. In order to achieve these goals, the main element is to understand who the customer is. It might be a single customer or a group of customers depending on the characteristics of the product and the volume demanded.

Ideally, each customer would have a dedicated value stream. This approach would enable the management to focus on the product rather than focusing on functions or departments. In this way, the system becomes more responsive and problems are more easily traced to their root cause. It is often the case that a few products are only minimally different from each other. Such a group of products belongs to a product family that share many components and differ only on small variations. In this case, the similarities call for a product family to be grouped into a single value stream to avoid infeasible investments and to capture any economies of scale. The calculation of takt time (See step 4) for a product family involves the aggregate demand for all product variations.

Once the customer is identified, the capacity of the system must be decided. At this stage, only the long-term capacity strategy is considered, the next step explains in more detail how to cope with temporary demand fluctuations. The problem of capacity planning resides in the forecast of the demand that the system will experience when it is finally installed. The problem is magnified as the production system design lead-time increases [Charles, Cochran and Dobbs, 1999]. Figure 2-4 shows the uncertainty in the demand forecast and the probable distribution of the actual demand.



Charles, Cochran and Dobbs, 1999

Figure 2-4: Uncertainty in demand forecasts

Another decision that must be made at this stage that is closely linked with the capacity problem is capacity increment to implement. The size of the capacity increments that can be achieved by different types of production systems plays an important role in this decision. For example, a high-speed transfer line might be a good candidate for a particular process but only if the demand is known with great certainty. Transfer lines are very efficient but lack volume flexibility. Furthermore, capacity can only be added in large increments (i.e. another transfer line) and it takes a long time to implement. On the other hand, manufacturing and assembly cells easily adapt to temporary demand fluctuations. Additionally, a cell usually has a small capacity and the lead-time to implementation is short. Figure 2-5 shows the capacity planning capabilities of the two manufacturing systems.

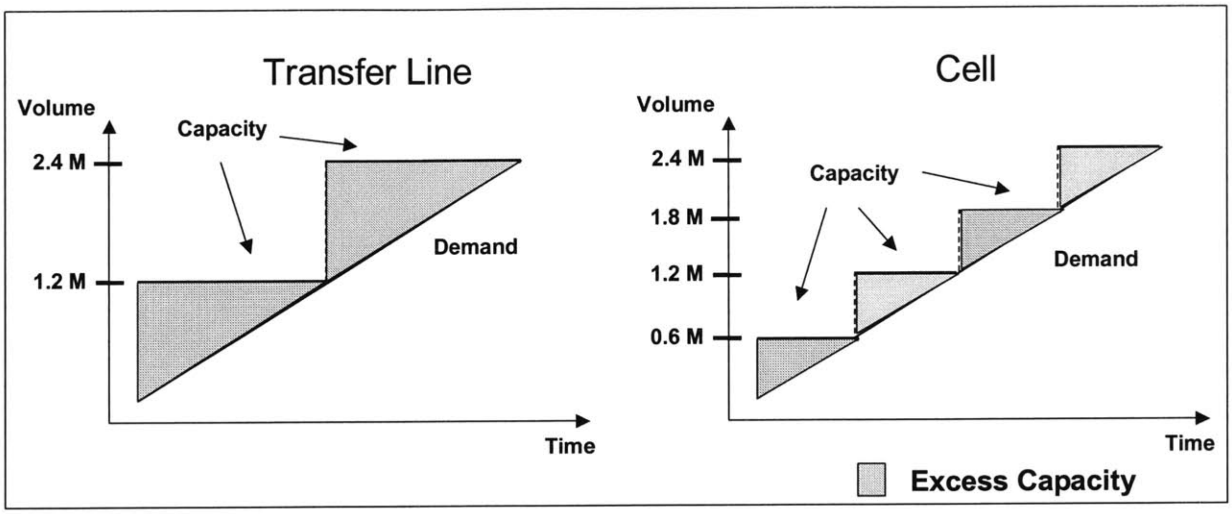


Figure 2-5: Capacity implementations over time

2.4 Step 4: Define customer Takt time (subject to > 30 seconds)

One of the most important aspects of manufacturing system design is defining the takt time and using it effectively. The term "takt time" comes from the German word "takt," which refers to the rhythm and time bar in a piece of music. In the context of manufacturing it is used to refer to the pace of customer demand, at which products are manufactured. Takt time is a concept that relates the customer demand to the available time to produce the required goods. As such, takt time is an essential tool to pace the production and has a strong influence in the design of the manufacturing system. It affects many aspects of the system like the general layout, machine design (cycle times), work loops and even the size of containers to transport the materials. The role that takt time plays in the design of these elements will be further explored in the subsequent steps.

Takt time is a representation of the average quantity demanded by the customer in a given period of time. It also defines the time available to produce one part [Shingo, 1981]. It can be defined as the overall available production time in a chosen time interval divided by the overall forecasted customer demand for the time interval [Linck, Cochran, 1999]. Takt time can be calculated according to the following formula:

$$TaktTime = \frac{TimeAvailable}{AverageCustomerDemandperTimePeriod} \qquad (6)$$

where,

$$TimeAvailable = TotalTime - (MaintenanceTime + TimeAllowances) \tag{7}$$

The *Total Time* represents the complete working time that has been scheduled for production in a given period (i.e. one day, one week, etc.). The *Time Available* is the *Total Time* less breaks and scheduled allowances for that period. It can also include a factor for changeover and downtimes. To determine the *Average Customer Demand per Period* the customer for the system must be defined as was described in step 3.

Note that the calculation of takt time involves the *AverageCustomerDemandperPeriod* but the actual demand will probably vary with time in some type of normal distribution. The actual takt time also follows these variations and must be calculated for every period. Figure 2-6 illustrates this concept. In order to accommodate for these variations, the cell and in particular the equipment, must be designed to handle a range of takt time. Figure 2-7 shows how the distribution in demand affects the takt time. This idea is described in more detail in Step 6.

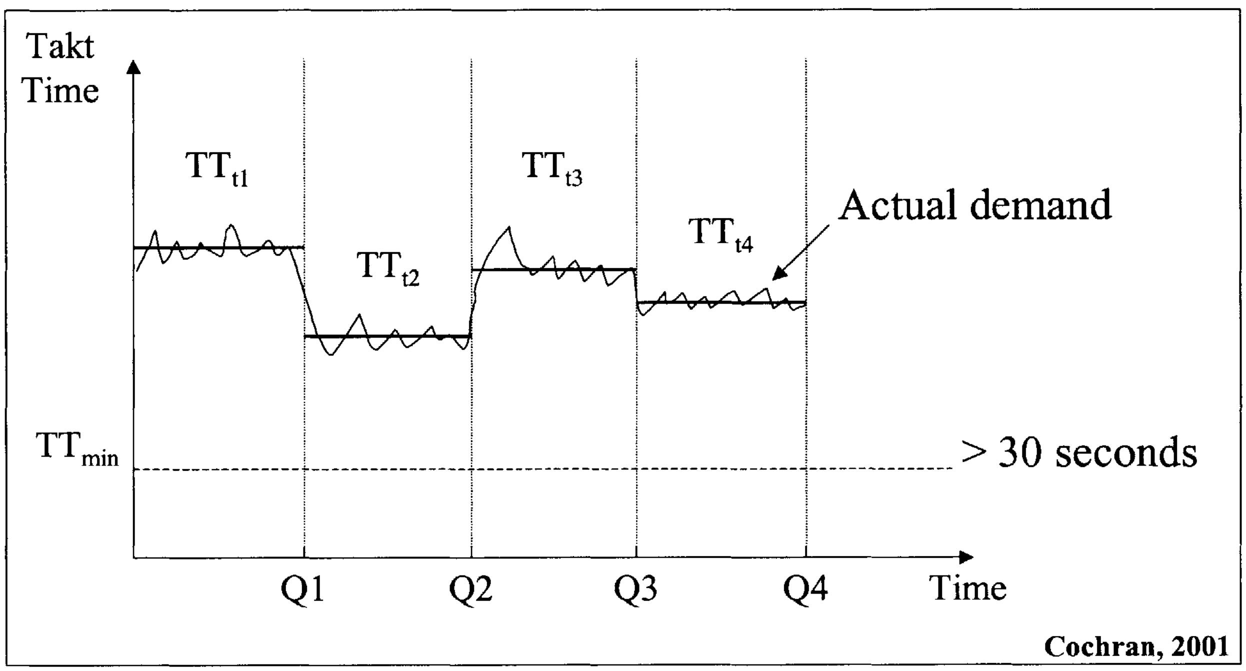
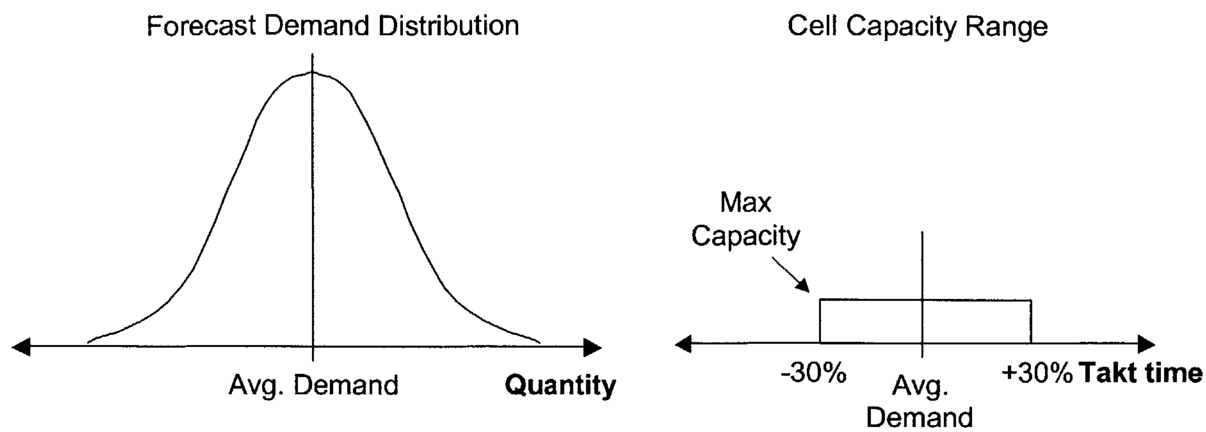


Figure 2-6: Takt times determined by the average demand for each period



Adapted from Cochran and Milby, 1998

Figure 2-7: Demand distribution and resulting cell capacity range

Since the takt time will pace production, every subunit, workers included, must complete its operations performed on the parts in that time. Therefore, a takt time faster than 30 seconds will lead to high-speed, specialized equipment and will bind workers to one machine. It will be seen in the discussion of the next steps that volume-flexible cells require workers to operate more than one station, therefore it is recommended that the takt time be greater than 30 seconds.

2.5 Step 5: Define the linked-cell system flow

In order to maintain a holistic view of the system, it is necessary to create a value stream map. Once the objectives for the manufacturing system have been understood, and the customer and demand have been identified, it is possible to define the value stream flow of the manufacturing system. The production flow is composed of two equally important elements, the physical material flow and the information flow. It is easy to understand why it is important to define a particular path for the material to flow. But the information flow must be treated in the same way. The system elements must have the relevant production information at all times. In particular, knowledge concerning the demand volume and mix as well as timing is required at each step of the flow.

Value stream mapping is a tool that has proven to be effective in capturing the most important information regarding a manufacturing system material and information flow [Rother and Shook, 1999]. The flow of the entire manufacturing system is identified and is usually represented graphically. The value stream comprises all the activities that are required to bring a product to the customer. The activities include those that add value to the product and also those that do not add value whether they are necessary or not (waste). Figure 2-8 illustrates the basic symbols of value stream mapping.

Mapping the flow in this manner enables the designers to maintain a broad perspective of the system. Additionally, a value stream map facilitates the visualization and eventual elimination of the seven types of waste identified by Ohno: overproduction, inventory, unnecessary production steps, unnecessary transportation, waiting, unnecessary motion and making defective parts that require rework. [Ohno, 1978].

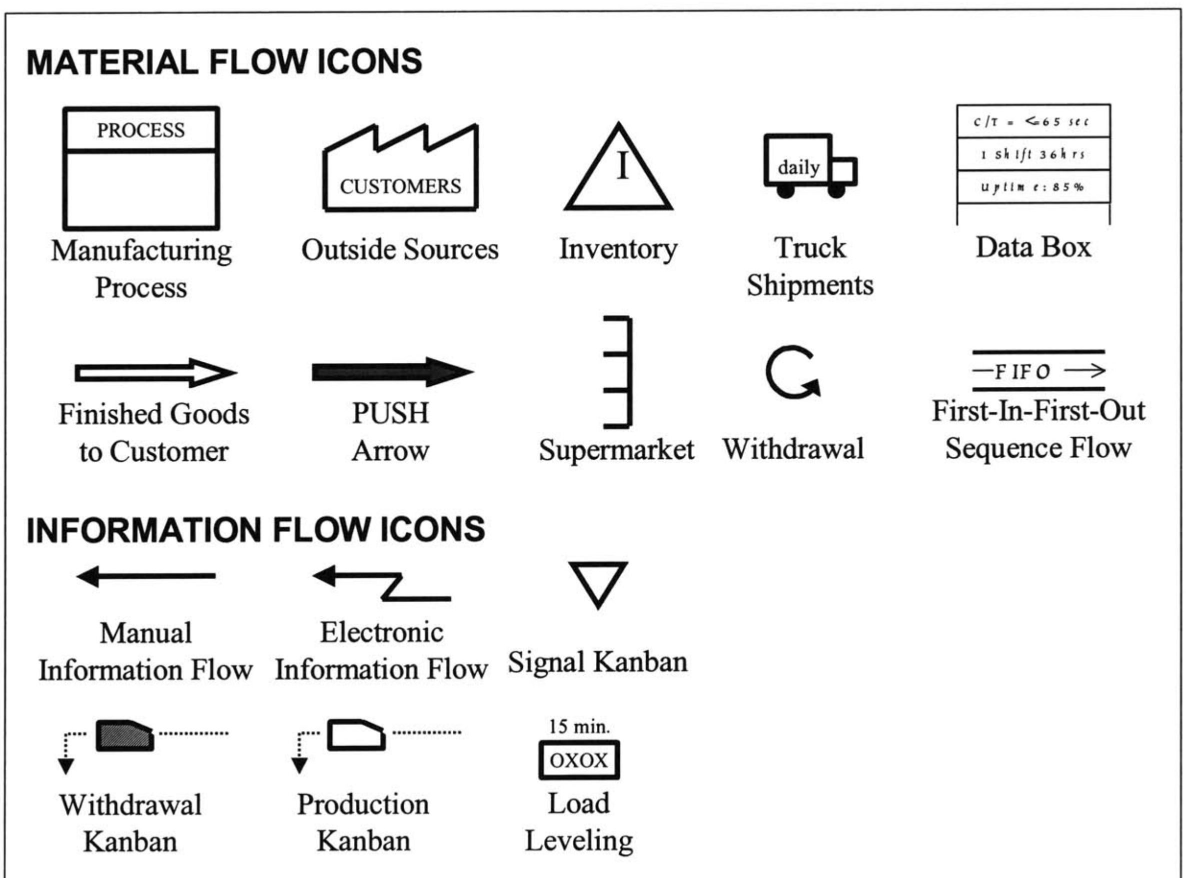
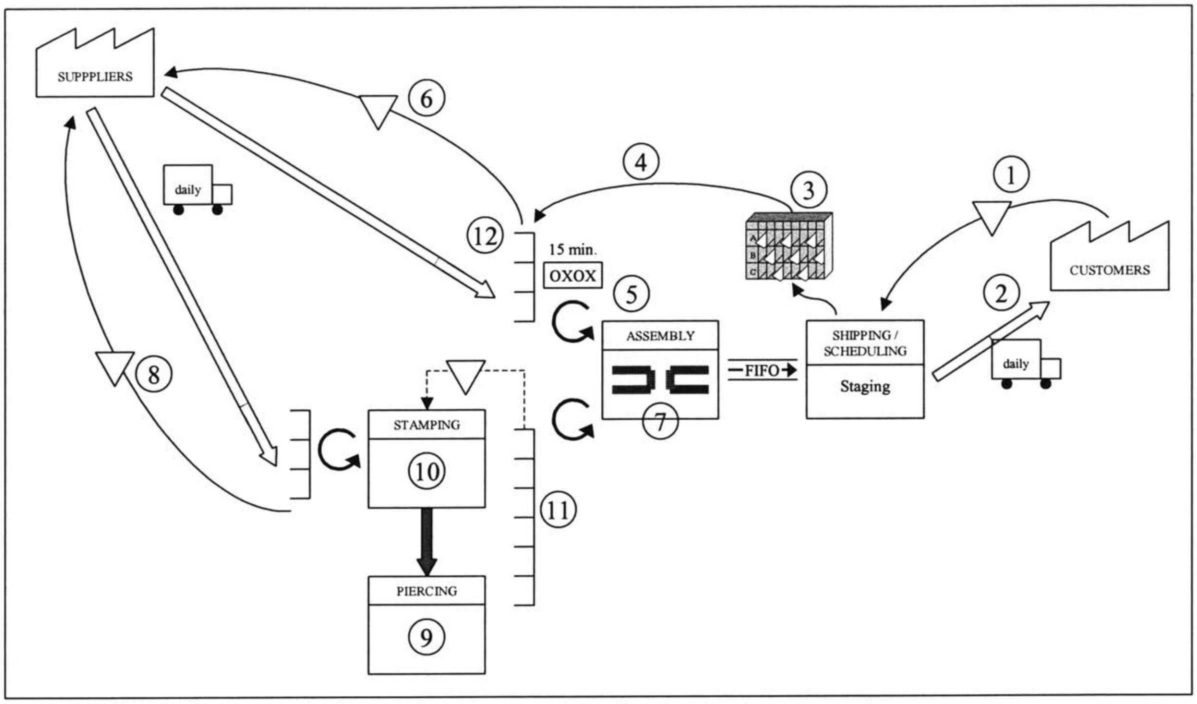


Figure 2-8: Basic Value Stream Mapping Icons

The value stream for a product can include all the steps from extraction of the raw materials to the distribution channels to the final retail sale point. Some cases might call for such an extensive mapping, but in this case the interest is focused on what happens within the limits of the manufacturing system in question. At this stage, the map should be simple and limited to a level of detail that is in line with the overall system. At this stage, there is not enough information yet to define finer elements like the size of the intermediate buffers or Standard Work In Process (SWIP) between operations, although their location in the system flow should be designated at this point. Figure 2-9 illustrates an example of a value stream map that represents the future state of a manufacturing system.

Due to the importance of information in the manufacturing system, it is important to consider the manner in which it will be distributed. There are two main designs that lead to either a push or pull system. In a push system, a central production-planning department creates an independent schedule for each of the processes based on actual demand but without considering the state of the system. Each operation is responsible for fulfilling the schedule requirements and supplying the products to the subsequent operation. Under this system, the central planning unit must process any unexpected changes in demand volumes and a new schedule must be issued. This process is usually long and requires large variable buffers between processes. As a result, production lead times and throughput times are unnecessarily long.

The pull system, pioneered by Toyota in Japan, uses a single production schedule that is issued to the final operation (usually final assembly). This operation withdraws the required materials from the preceding processes to complete the schedule. As a result, the upstream operations produce only what has been withdrawn. In this way, the entire manufacturing system is controlled with a single schedule and production is strictly limited to what is needed. Inventories between processes are kept to a minimum and most importantly are standardized. The simpler pull system generally has a shorter lead-time and throughput time; moreover it has the added benefit of predictability due to standardization. There are several methods to implement a pull system: Kanban, CONWIP, etc. Step 9 includes a detailed explanation of these techniques.



Mierzejewska, 2000

Figure 2-9: Value stream map example

2.6 Step 6: Form cells based on takt time

2.6.1 Forming Cells (cells vs. Other)

This step is concerned with the details within each of the manufacturing subunits defined in the system value stream. The specifics concerning the individual stations or processes are defined. But before this is done, a decision must me made regarding the type of manufacturing units that will be implemented. There are a few different widely used subsystem types; each one has its advantages and inconveniences that will be explained below. These systems are presented for reference only, and not as a list that defines the only possible choices from which the designer must pick one. The manufacturing subunits that will compose the overall manufacturing system must be designed with specific requirements in mind. It is not likely that these requirements will be fully satisfied by any one particular system type. The best solution will most likely be a hybrid containing elements of several different system types as well as some original elements.

Charles, Cochran and Dobbs describe each type of manufacturing system and categorize them according to the production environment in which they are more efficient. Table 2-2 shows this classification [Charles, Cochran and Dobbs, 1999].

Table 2-2: Characteristics of manufacturing systems

	Volume Certainty	Product Mix	Product Life
Automated Transfer Line	High	Low	Long
Job Shop	Low	High	Short
FMS	Medium	High	Short
Agile Cellular	Medium	Medium	Medium
Lean Cellular	Low	Medium	Medium

Automated Transfer Lines

Manufacturing systems using dedicated automation use machines that were specially designed with a particular model of a product in mind. Dedicated automation is most effective for products that have a constant demand. This is because the majority of costs associated with these systems are fixed. Examples of dedicated automation include traditional American automobile engine production lines and automotive component assembly lines.

Advantages:

- High volume capacity.
- Cost effective for products with long life cycles.
- Most profitable at the production level for which they were designed.

Disadvantages:

- Expensive due to the engineering and custom development required.
- Low product mix flexibility: generally support very few different products or models.
- Low volume flexibility: relative high cost to retool.
- Production cost highly sensitive to variations in demand.

Job Shop

A Job Shop style manufacturing system uses standard flexible machines that are not oriented or configured for any particular product. Instead, products flow from machine to machine in which ever order is necessary. Parts are not automatically transferred from one machine to another. Job Shops generally produce in batches. For instance, a batch of 100 parts of a particular type is processed at one machine and then the batch is transported to the next machine.

Advantages:
- Highly flexible. Able to produce a large product variety even in low volume products.

Disadvantages:
- Long changeover times.
- Complex scheduling.

Flexible Manufacturing System

A Flexible Manufacturing System (FMS) is essentially an automated Job Shop [Black, 1991]. The machines are organized in a similar way and support a wide variety of products. Generally, material transport between machines is automated with robots or Automated Guided Vehicles (AGVs).

Advantages:
- Supports a high product variety.
- Automatic changeovers.
- Better handling of delicate parts.

Disadvantages:
- Large initial investment.
- Difficult to change over.
- Difficult to identify problems.

Agile Cell

Agile Cells consist of clusters of modular machines which function in a similar manner to an FMS. Agile cells conform to the RRS Design Principles: Reusable, Re-configurable, and Scalable [Dove, 1995]. The modular machines are built around a common architecture. To date, Agile Cells have been utilized primarily in electronics fabrication where high equipment cost, short product life cycles, and delicate part handling are necessary.

Advantages:
- Highly flexible. Reusable, Re-configurable, and Scalable by using modules.

Disadvantages:
- Modules fix designs around a particular technology.

Manufacturing Cell

Manufacturing Cells are often associated with the Toyota Production System (TPS). The workers in a cell are capable of operating multiple stations. Generally the operators transport the material between operations. Sometimes a simple manual conveyor is used if the part size and geometry justifies it. In a manufacturing cell, machines are capable of detecting abnormalities and stop to prevent defects from being made.

Advantages:
- Volume flexible by adjusting the number of operators (no hardware changes required).
- Product mix flexible.
- Workers have more control.
- Operator flexibility is harnessed to achieve fast changeovers.
- High potential for improvement.
- Low initial investment

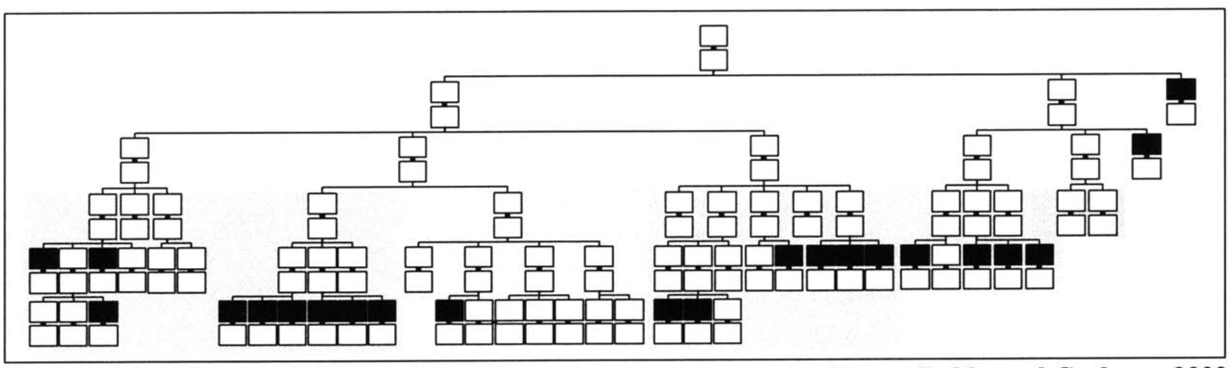
Disadvantages:
- Might not be the most cost effective if demand is fixed.
- Requires a skilled workforce.

It is clear that the manufacturing cell is the most flexible system both in terms of volume and product mix. Furthermore, the initial investment required is usually lower than with any of the other systems described above. These characteristics enable the manufacturing cell to achieve a low cost and high quality simultaneously. Additionally, it is a straightforward system that does not require complex scheduling methods. The simplicity of the machines used (see the following section on equipment selection) also makes it a highly reliable system and facilitates its maintenance. For these reasons the manufacturing cell will be used as the basis for the design of the manufacturing subunit throughout the rest of the document. Nevertheless, the particular requirements of the manufacturing system in question will ultimately shape the best solution for its manufacturing subunits. The following sections assume the cellular form as the production subsystem in their discussions.

2.6.2 Equipment Design/Selection

The manufacturing subsystem that is comprised of the equipment is a very important element of a production system. In most processes, it is the equipment that modifies the material to add value to the customer. The design and selection of this equipment plays an important role in the overall system because it can determine its ability to meet the higher-level objectives of the organization.

Gomez, Dobbs and Cochran identify a subset of requirements from the MSDD that influence to the design and operation of the manufacturing equipment. These FR's provide a clear guide for the selection of the machinery in order to provide the capability to the system to achieve the overall manufacturing strategy [Gomez, Dobbs and Cochran, 2000]. The subset of requirements is shown in Figure 2-10. In the spirit of simplicity and practicality, the original 22 FR's where consolidated into the 13 requirements presented in Table 2-3.



Gomez, Dobbs and Cochran, 2000

Figure 2-10:FRs from MSDD that Affect Equipment Design and Operation

Table 2-3: FRs that affect equipment design and operation arranged by area

Area	Functional Requirements
Quality	FR-Q11 Eliminate machine assignable causes:
	FR-Q13 Eliminate method assignable causes:
	FR-Q123 Ensure that operator human errors do not translate to defects:
Time Variation	FR-R11 Rapidly recognize production disruptions:
	FR-R12 Communicate problems to the right people:
	FR-P121 Ensure that equipment is easily serviceable:
Delay Reduction	FR-T22 Ensure that production cycle time is balanced with takt time:
	FR-T32 Produce in sufficiently small run sizes:
	FR-T5 Reduce systematic operational delays:
Direct Labor	FR-D11 Reduce time operators spend on non-value added tasks at each station:
	FR-D2 Eliminate wasted motion of operators:
Facilities Cost and Production Investment	FR123 Minimize facilities cost:
	FR13 Minimize investment over production system lifecycle:

These requirements and their corresponding design parameters in the MSDD can be expanded into a set of guidelines for the design and selection of equipment. These guidelines are meant to point out the important requirements and not the solution. Although some solutions are presented as examples, the actual solution should be specific to the application. The following suggestions are grouped into the five areas identified on Table 2-3.

Quality

1. Provide the equipment with failure mode and effects analysis capabilities. Gauges should provide feedback for automatic adjustment of processes.

2. Include mistake-proof devices (Poka-Yoke) to prevent operator induced defects

Time Variation

1. Enable the operator to detect disruptions by providing standard signals that indicate both the presence of a problem and its nature (Andon boards, emergency lights, etc.).

2. Create a standard procedure for reacting to every type of disruption. It should dictate the reaction procedure as well as the steps to convey information to the right players (operator, maintenance, management, etc.).

3. Design for serviceability: Place service access panels where they are easy to reach (provided they don't interrupt the work), the equipment should provide information about the nature of the problem, avoid the use of specialized tools where possible, etc. See Figure 2-11.

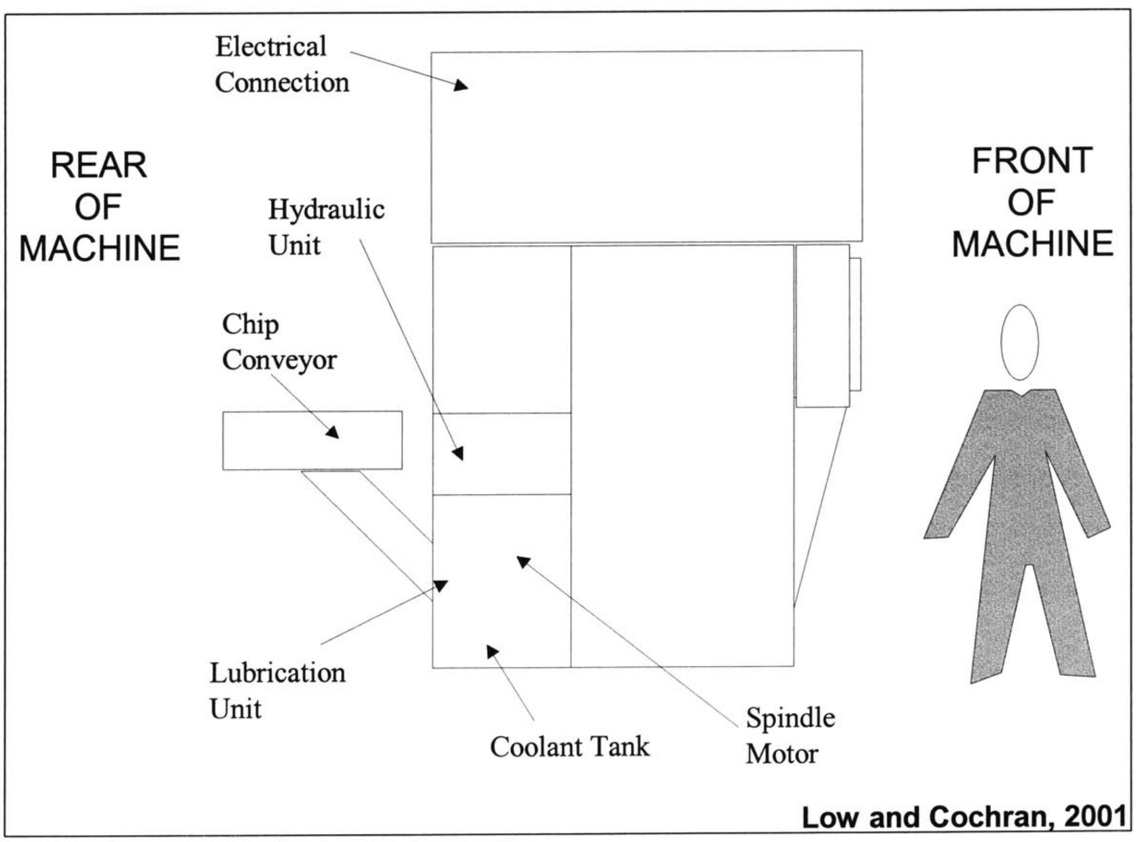


Figure 2-11: Design for serviceability: access to machine does not interrupt the work

Delay reduction

1. Automatic processing time should be designed to meet the desirable range of takt time. Remember takt time should always be greater than 30 seconds (see step 4).

2. Design for quick changeover. See step 7 for more details.

3. Design access for support activities separate from operation access (Maintenance, adjustments done by someone other than the operator, material feeding must not interfere with operator, etc). Figure 2-12 shows an example of unobtrusive material feeding.

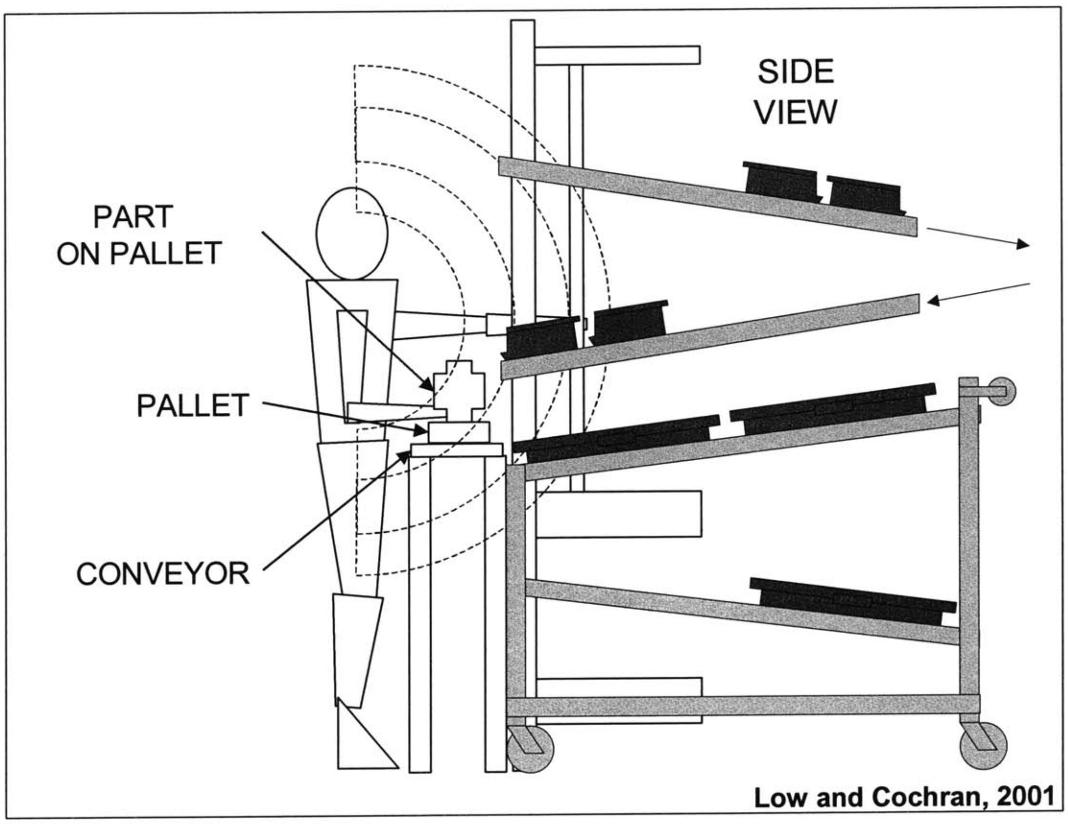


Figure 2-12: Unobtrusive material feeding

Direct labor:

1. Equipment should enable the separation of the worker from the machine. This is frequently achieved through autonomation. Autonomation refers to the capacity of a machine to run automatically and distinguish normal from abnormal operating

conditions. If there is an abnormality present, such a machine will stop operating [Ohno, 1978]. The worker is still expected to select appropriate solutions and execute them [Shingo, 1981].

2. The equipment should be designed to facilitate operator's tasks. The goal should be to minimize the non-value added motions of the operator. Examples of this idea are machine small face print (i.e. narrow width) to reduce walking distance, using walk-away switches, keeping all needed tools within reach of the operator and having an ergonomic interface between the machine and the operator.

3. If the unload of the finished part with one hand and load of the new part with the other cannot be performed, provide an additional redundant fixture or de-coupler.

Investment

1. Reduce the footprint of the machine to minimize the floor space required.

2. Equipment should be purchased to last throughout the expected life of the product.

3. Equipment should be able to be re-configured and easily moved in case the product design changes or there is a need to produce a different part (no special floor installation, avoid complex conveyors that prevent re-configuration, etc.).

4. Use standard off-the-shelf equipment instead of custom designed machines when possible to reduce initial investment and costs of maintenance.

2.6.3 Cell Layout Design

The cell layout design has a strong effect in the manner in which the work is conducted within the cell. The objective is to minimize the waste in the form of unnecessary motions caused by the layout. The layout design also represents a great opportunity to include elements that facilitate the operation of the cell.

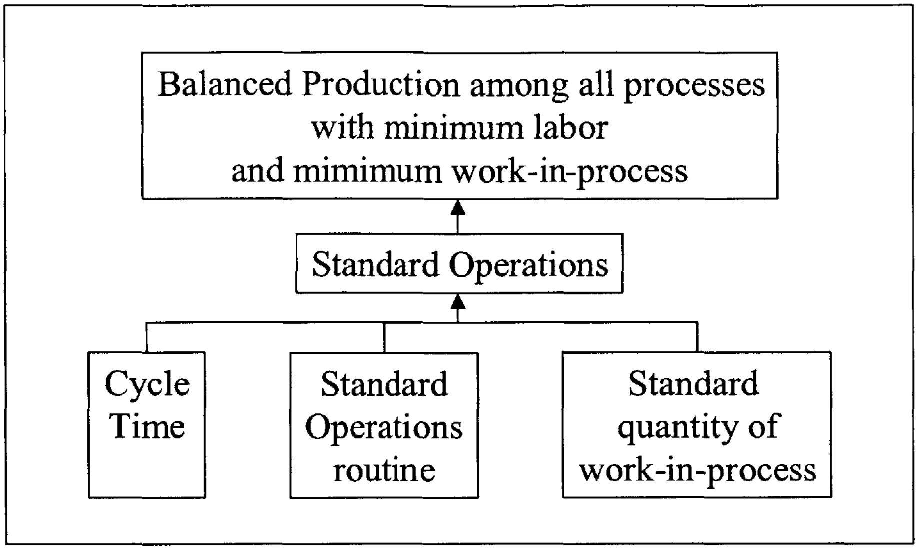
The equipment should be arranged in two parallel rows. This plan promotes man-machine separation by allowing the worker to access twice as many stations in the same area. It facilitates the balancing and re-balancing of the work, which enables the ability to achieve labor productivity while producing at takt time and makes volume flexibility possible. In order to reduce the walking distance between operations, the narrow width machines must be designed so that they can be placed next to each other with zero clearance and no obstructions should be placed in the walking paths. Additionally, to avoid the incoming material from increasing the walking distance it should be fed from the outside of the cell, typically above the work stations.

An important element to consider at when designing the cell layout is the working environment that it creates. For example, the illumination of the workplace has been proven to influence the productivity of the workers. In a cell that is designed as two parallel rows of equipment it is necessary to place the light source directly above the cell corridor to ensure proper lighting conditions. The surrounding space can also have an effect in the workers well being, thus both ends of the cell should be left open for easy access and to avoid "caging" the operators. Other factors to consider are noise, cleanliness, safety, etc.

2.6.4 Standardized Work Methods

Standardized work methods are an essential part of a cell production unit. A standardized work method is the best-known method at the time that the operator must follow. It explicitly describes the details of how the work must be done by the worker. It is important that the operator actively participates in the development of the standardized work methods. The elimination of waste, and improvements in general are only possible through the standardization of the work [Onho, 1978]. Defining the work method enables the existence of a baseline from which to improve. In the absence of consistency between workers, one can only hope to improve the performance of a single operator rather than advance the state of the entire operation of the cell. As improvements are made, the standard is revised and the improvements are incorporated into the new method. Furthermore, homogeny in the production methods ensures a predictable output in terms of both time and quality.

A standardized work method conveys three types of information: cycle-time, standard operations routine and standard work-in-process. These three elements ensure that the goals of efficient work, balancing among processes and minimizing in-process inventories can be achieved [Monden, 1998]. Figure 2-13 shows the elements of standardized work methods.



Monden, 1998

Figure 2-13: Elements of standardized work methods

The cycle time of a standardized work procedure is equivalent to the takt time of the cell. As it was discussed in Step 4, it depends on the available production time and the average customer demand. As demand varies, the cycle time in the standard work procedure should be updated. It is worth noting that if there is a large enough shift in demand, the number of operators required to run the cell changes might change as a result of these adjustments. The selection of equipment with a capacity that can support a range of takt times enables this volume flexibility.

The standard work routine, also termed standard work combination, is formed with the sequence of actions that the operator must complete in one cycle. These actions include transporting parts from one operation to the next, loading and unloading machines and finally the manual work. The standard work routine can be recorded in a standard work combination sheet, which in turn can be used to study the work and eliminate inefficiencies such as waiting and unnecessary transportation.

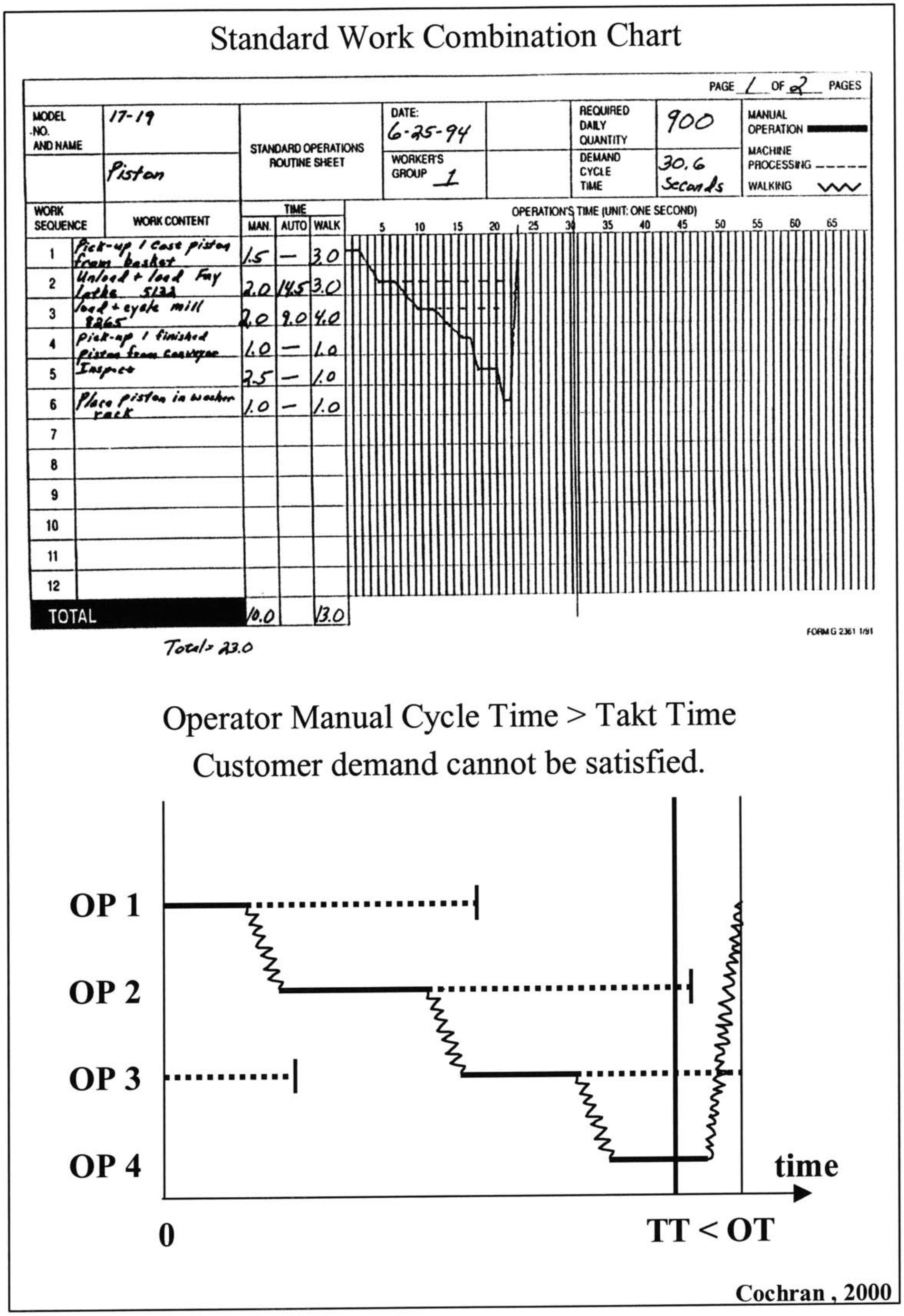


Figure 2-14: Examples of Standard Work Combination Sheets

The standard work combination sheet measures three different types of activities and assigns a time to each of them. First it records the automatic cycle time of each machine (man-machine separation is assumed) under the column labeled "Auto." This is the time that it takes each piece of equipment to fully process one part and is represented with a horizontal dashed line. The sheet also records the manual work performed by the operator at each station under the column labeled "Man," which includes unloading the finished part, loading the new part and any other activities required before walking to the next operation. This time is displayed as a horizontal solid line. Finally, the sheet accounts for the time spent walking from one station to the next. This time is represented by a squiggly inclined line and is recorded under the column labeled "Walk." Figure 2-14 shows an example of a Standard Work Combination Sheet in which the operator is not able to finish all the activities under the takt time.

In order to produce the parts in the time allowed, the production cycle time must be equal or less than the minimum takt time (See Step 4). Therefore, both the automatic work done by machines and the manual work of operators must be completed under this time. The standard work combination sheet is a great tool to ensure that this requirement is met. It can also be helpful in balancing the operations to avoid process delay.

A balanced production system can be defined as a system in which all operations or subsystems run at the same cycle time (ideally the cycle time would be less than or equal to takt time). Balancing production is important to avoid the build-up of work in process between operations that causes process delay. This phenomenon occurs when the arrival rate at an operation is not in line with the servicing rate. Figure 2-15 illustrates the effects of a balanced and unbalanced system.

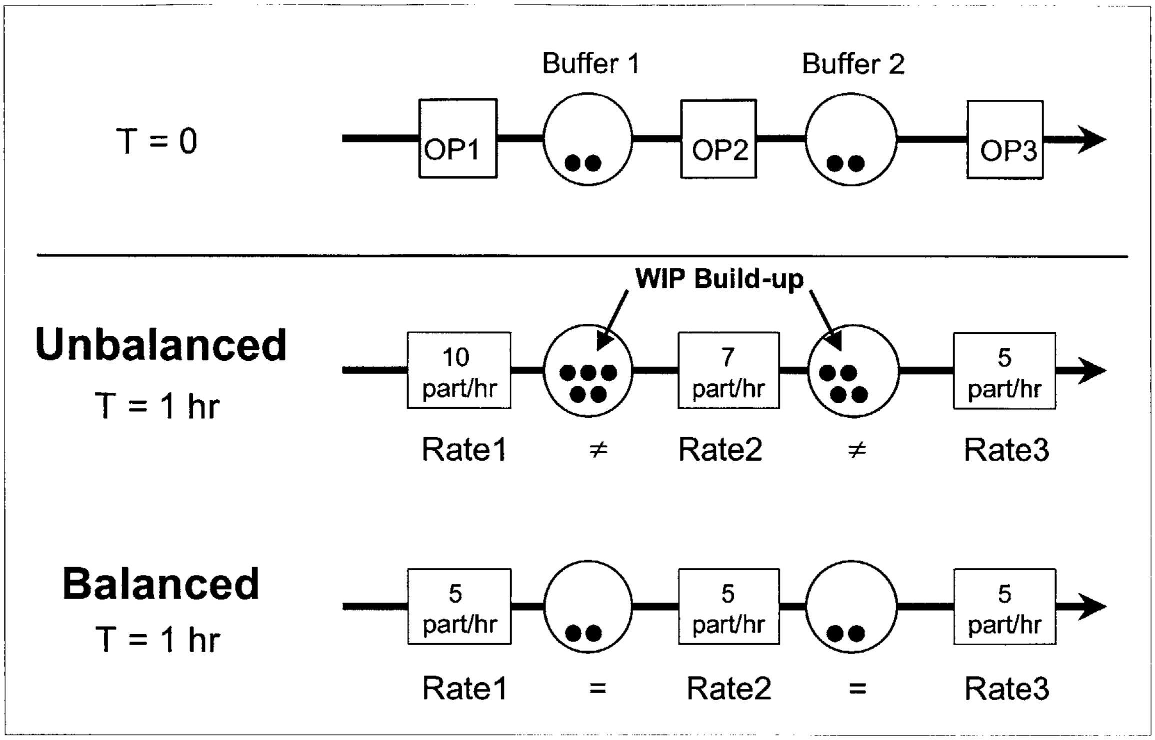


Figure 2-15: Illustration of balanced and unbalanced production

Finally, the term "standard quantity of work-in-process" refers to the minimum intra-process work-in-process needed for operations to proceed. This includes items mounted on machines [Shingo, 1981]. Usually, there is no need to have parts in between individual operations unless one of the machines processes two parts at a time. Thus, the standard quantity of work-in-process that is needed consists of the parts loaded on the machines.

2.7 Step 7: Reduce setup time

This step is of high importance because it provides the capability for achieving leveled production in the next step. Without reducing the setup time the manufacturing system is constrained to large run sizes (run size is defined as the number of consecutive parts of the same type produced before changing over to another type) because the time lost in changing over the equipment would be prohibitive. The importance and advantages of leveling production will be discovered in the next step.

The need to reduce the setup and changeover times of equipment was first recognized by Shigeo Shingo. He proposed an approach to this problem and named it Single Minute Exchange of Die or SMED [Shingo, 1985]. Since then, there have been several other variations like One Touch Exchange of Die (OTED) or Rapid Exchange of Tooling And Dies (RETAD) by J.T. Black [Black, 1991]. The approaches might differ in the details, but they represent the same basic idea of modifying the equipment and setup procedures to reduce the setup time of equipment.

Monden describes the four basic concepts to minimize the setup time. These concepts serve as a guide to develop a specific solution to each unique case.

Concept 1: Separate the internal setup form the external setup. Internal setup is defined as the actions that require the interruption of production. On the other hand, external setup refers to all the other setup activities that can be done without disrupting the operation of the equipment. It is important that these two activities be separated in such a manner that the equipment operator is never responsible for performing any of the external setup actions. These activities must be previously completed prior to initiating the setup maneuver.

Concept 2: Convert as much as possible of the internal setup to the external setup: This concept is regarded as the most important one of the four. It consists of devising any changes to the equipment or procedure that would eliminate internal setup or would make it possible to or perform as much of it without interrupting the operation. Examples of the application of this concept include preheating dies, standardizing tool sizes, etc.

Concept 3: Eliminate the adjustment process: Adjustment usually takes as much as 50 to 70 percent of the total internal setup time, therefore eliminating it is a priority. Adjustment is the process of fine-tuning the process until the first good part is produced. It is often an iterative process that is time consuming and produces a considerable number of defective parts. Figure 2-16 shows a schematic representation of the setup process.

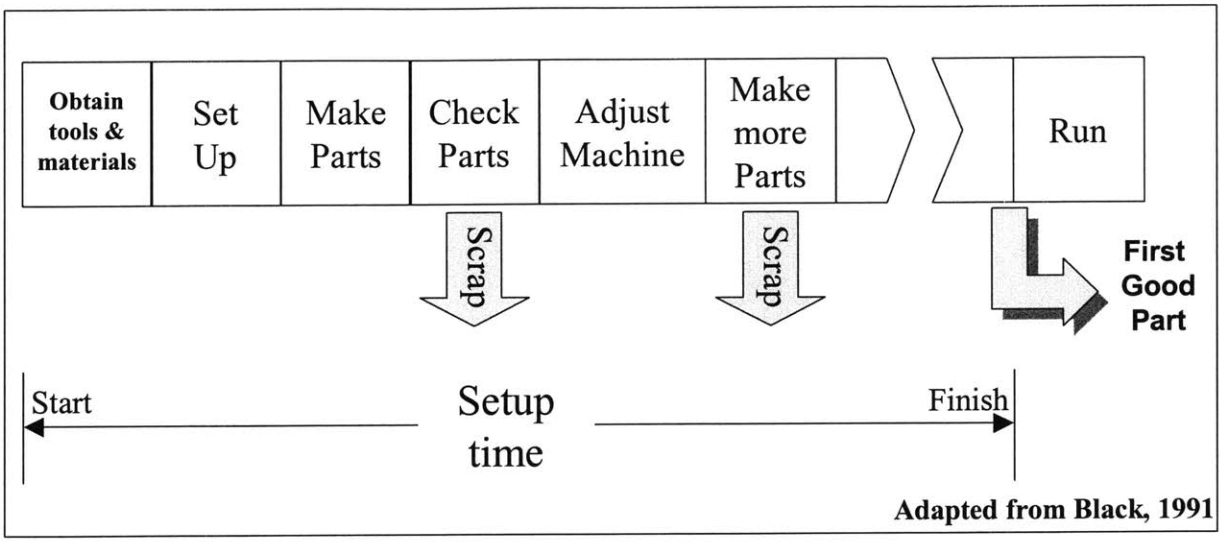


Figure 2-16: The role of adjustment in the internal setup process

Concept 4: Abolish the setup step itself: There are three methods to completely eliminate the setup process itself. First, at the product development stage, products can be designed so that they have parts in common, reducing the number of special parts. Second, produce the different parts at the same time. The second approach requires equipment capable of handling several part types at the same time. For example, a die can punch out two different parts with a single stroke. Finally, if the equipment is simple and inexpensive, there could be redundant machines or tools; one for each part type. In this case, the set up would consist in simply using the right piece of equipment without making any modifications.

2.8 Step 8: Level final assembly – reduce the run size

Leveling production is defined as producing the quantity and mix of products demanded by the final customer within a specified time interval. Leveling consists of reducing the run sizes to achieve two goals: leveling the product mix and leveling the cycle time mix. In a true pull system, the leveling occurs at the pacemaker process, which is usually final assembly. The upstream processes produce what is pulled from their marketplaces, which is determined by final assembly. In this way, the entire value stream is effectively leveled and the consumption of each product type is kept constant in the upstream processes.

Leveling the product mix refers to the reduction of the run sizes in order to produce each part type in the quantity pulled by the customer during the demand interval. If the customer requires daily deliveries of a particular product mix the demand interval is one day. In such a case, a leveled production system must make each demanded part type in that day. Furthermore, the quantity of each product made daily should be equal to the quantity demanded by the customer. Figure 2-17 shows a leveled and an unleveled system. Note that in the unleveled case, the system is also able to meet the customer demand, but the disparity between production and demand causes the need to store and handle a large inventory. Additionally, the response time of the system is significantly lower. After producing the last product A after the second day, the system will not be able to produce another product A for another three days. If customer demand changes unexpectedly, the system will not be able to respond in a timely manner.

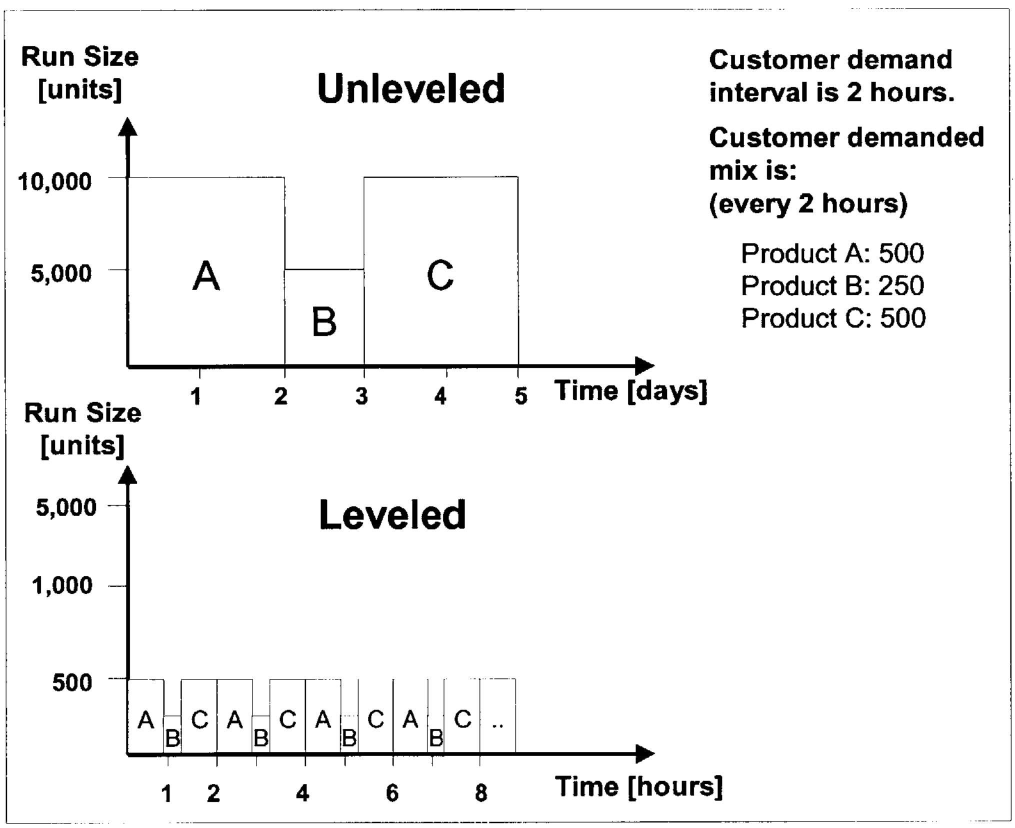


Figure 2-17: Leveling product mix to customer demand interval

Another type of leveling is leveling by cycle time mix. Leveling by cycle time is defined as smoothing the production of items that require different cycle times. If these differences in cycle time are not leveled, the system looses the ability to produce to the desire average takt time throughout the day and WIP might build between operations. These inequalities cause the system to become unbalanced and difficult to control. Figure 2-18 shows the variations in WIP caused by an unbalanced system. In this case, each process produces to full capacity, limited only by availability of parts (push). Note that the system is still able to meet the customer demand but overproduction occurs and WIP builds between operations. The system state of the system is constantly changing and it is difficult to predict its output.

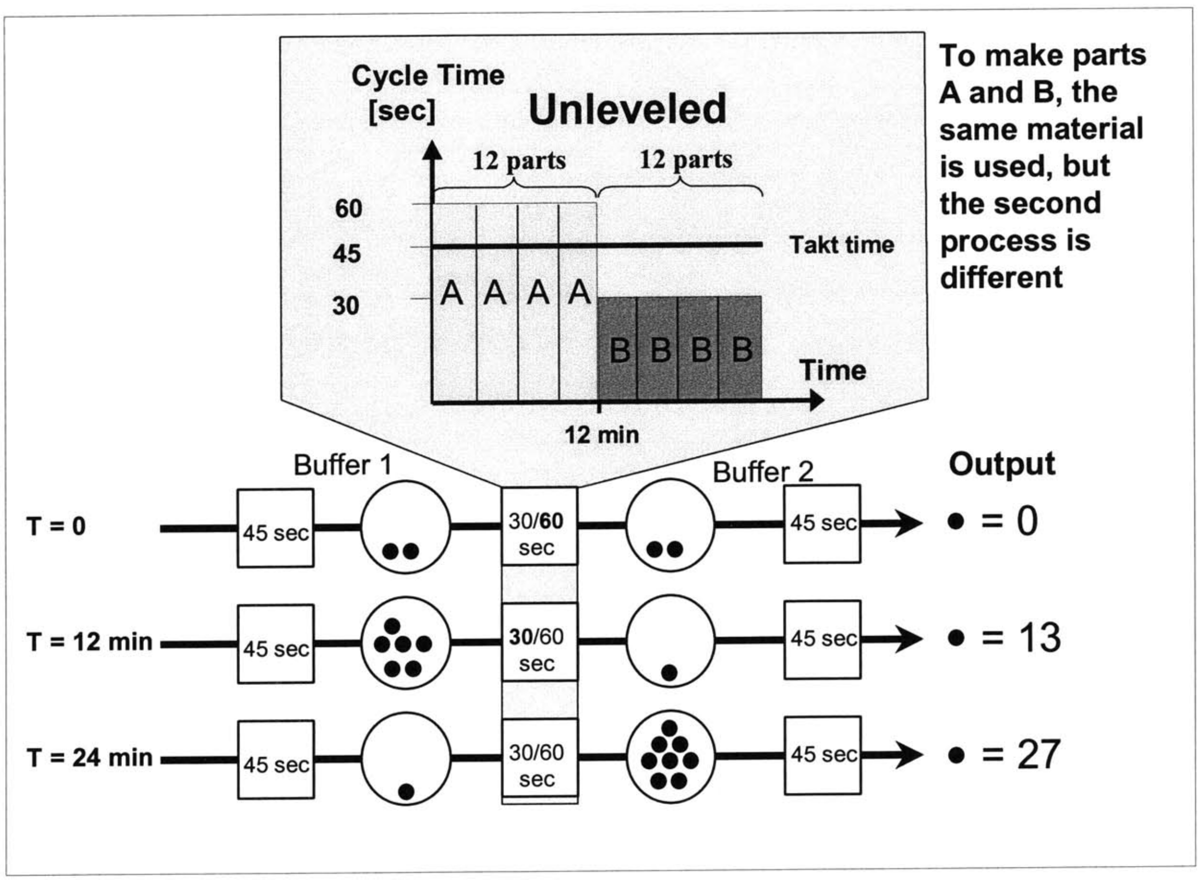


Figure 2-18: WIP variations caused by a system not leveled by cycle time

Heijunka is a tool that helps in the process of leveling and balancing production. The term Heijunka means "to level" in Japanese. Heijunka can be defined as distributing the production of different products with different cycle times throughout a period of time. As a tool, Heijunka is used to visually facilitate both, the leveling of product mix as well as leveling the cycle time.

A Heijunka box is composed of a grid of boxes designed to hold kanban cards or other production signaling instructions. The columns represent the production "time pitch." The time pitch effectively becomes the management time frame. The production subsystem is issued a production order every time pitch and in this way the monitoring frequency is also every pitch. The time pitch is a multiple of the takt time and is related to the standard container capacity:

$$TimePitch = TaktTime * LotSize \quad (8)$$

The rows in a Heijunka box represent the different product types. Each column holds one withdrawal card and the order is expected to be completed in the time pitch. In this way, the production subunit is paced and its progress can be visually inspected each pitch. Figure 2-19 shows a schematic representation of a Heijunka box.

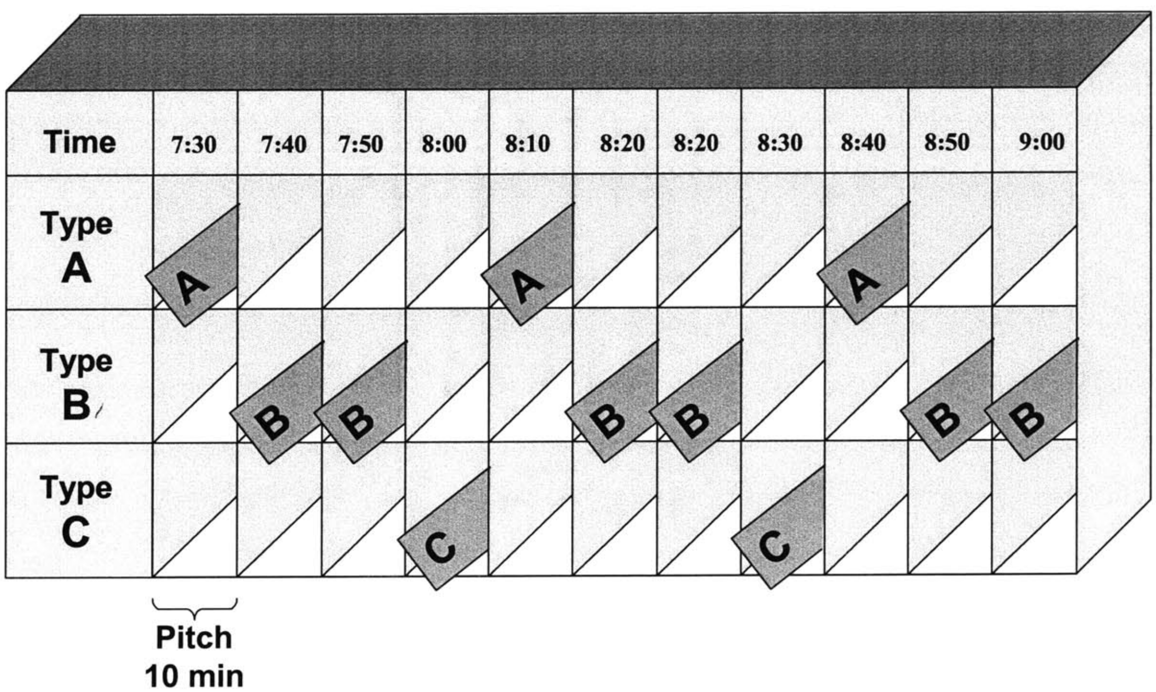


Figure 2-19: Heijunka box with three part types

The process of leveling production increases the number of changeovers in the equipment. For this reason, in order to achieve the benefits that are associated with leveling production it is imperative to reduce the setup times as described in step 7.

2.9 Step 9: Operate the linked system with leveling and pacing (Initially with large SWIP 'Standard Work in Process' between cells)

At this stage, the fixed hardware of the system has been designed. But before it can begin producing, the details regarding the relationship between the operations must be defined. In particular, the information flow to accomplish a pull system must be defined and the size of the Standard Work In Process (SWIP) must be determined.

A pull system can be achieved with several different techniques. In this section, the Kanban and Constant Work In Process (CONWIP) methods will be described. Each tool will be analyzed to find its advantages and weaknesses.

Kanban

Kanban is a tool for controlling production and inventory quantities within the plant. The word "Kanban" translates literally to "visible record" or "visible plate" but is more generally taken to mean "card." A Kanban is a card attached to a container that carries information for different purposes, the most widely used kinds can be classified into five types: withdrawal kanban, production ordering kanban, signal kanban, material requisition kanban and supplier kanban. Figure 2-20 shows a matrix that identifies each kanban type according to its function.

Since the kanbans are attached to the containers used to store and transport the parts, the desired size of the SWIP in the system determines the total number of kanbans used. Monden provides a series of algorithms to calculate the number of cards needed. The factors that influence the number of cards and hence the inventory level in the system are takt time, kanban cycle time, safety factor and container size [Monden, 1998]

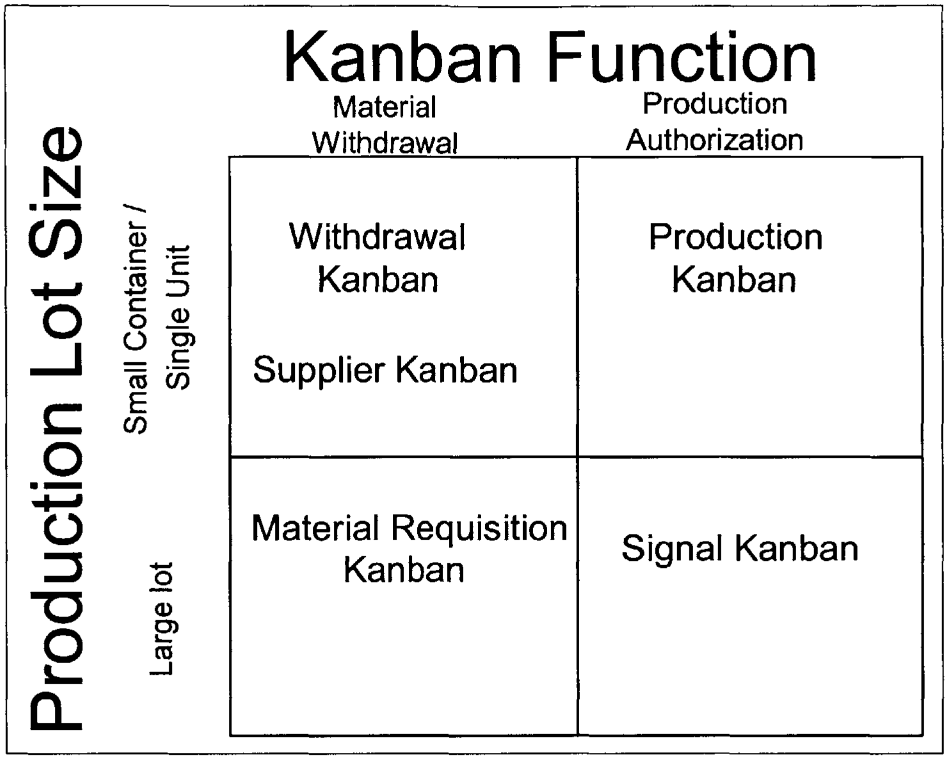


Figure 2-20: Classification of kanban types according to function and production lot size

Material withdrawal kanbans and production ordering kanbans are regularly used as complementary parts of the same system. The first is used to authorize the pickup of material and to initiate the transportation of the parts. A withdrawal kanban contains information concerning the part type and quantity required, the pickup location and the delivery point. Production ordering kanbans are used to signal the authorization to commence production. They convey information regarding the part type and quantity to produce, the downstream operation that requires the items and the production unit that will supply the parts. Although these two types of kanbans can be used separately, they are commonly utilized as shown in Figure 2-21.

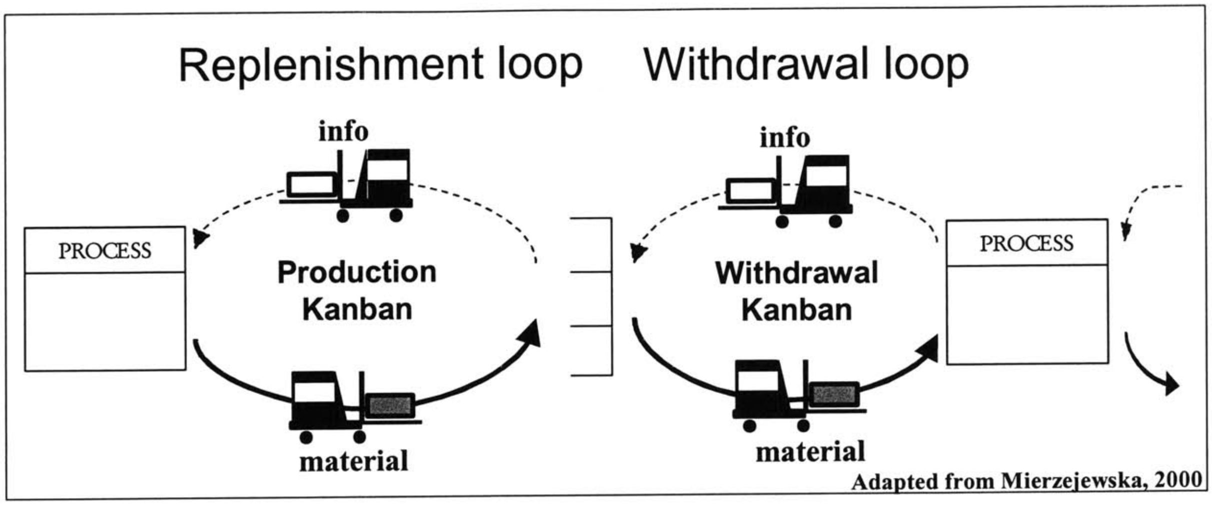


Figure 2-21: Kanban complimentary loops

Withdrawal and production kanban are use to link operations that have a similar cycle time and handle relatively small containers or run sizes. This system is convenient when frequent transportation of the material is possible. When the processes have a small cycle time and production run sizes are large the other types of kanbans are used. The withdrawal kanban is replaced by a material requisition kanban and the production kanban is substituted with a signal kanban. A signal kanban aggregates multiple orders and signals production when the desired run size is reached. Material requisition kanban is then used to obtain material required for production.

Finally, supplier kanban is used as a withdrawal kanban to authorize the shipment of material and parts from the supplier. The difference between withdrawal and supplier kanban is that in the supplier loop, the supplier is responsible for the delivery of the products. Additionally, the supplier kanban can transmit information that is necessary for the financial transactions between supplier and customer.

CONWIP

The idea behind CONWIP is to establish a limit on the WIP that is present in the system. It signals production at the beginning of a process flow and keeps track of the state of the system. If the quantity of WIP in the system has reached the predefined limit, it stops the production orders until the WIP is reduced. CONWIP is very similar to the Kanban system; the main difference is that in CONWIP the signal is given to the first process. In doing so, it is assumed that the line does not experience any variations that affect the right quantity of the right mix. If variations are present or if the line produces a significant amount of scrap, the orders are never completely fulfilled and the schedule has to be constantly modified. Figure 2-22 shows an example of a CONWIP system.

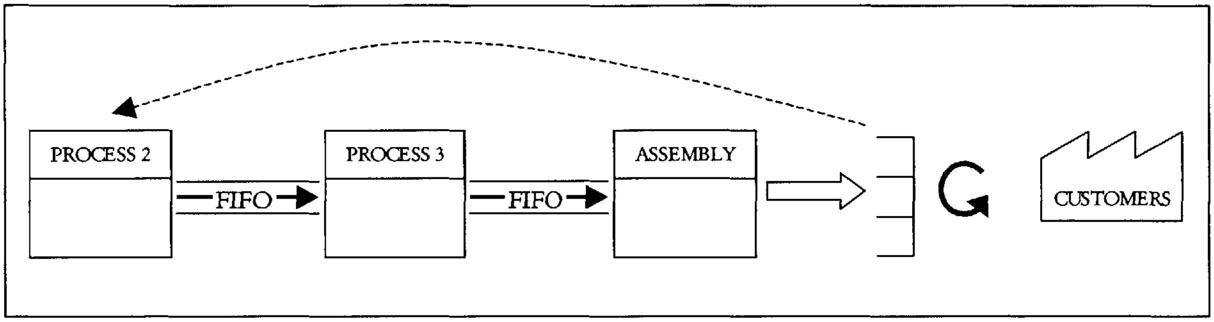


Figure 2-22:CONWIP pull system

Work in process (WIP) within the system is necessary to decouple operations and ensure that the system is stable even though there is variation in the operations. It is desirable to minimize the size of the WIP to reduce the holding costs as well as for increasing the system's responsiveness. It is more important however, to control and standardize its levels. This standard should be dynamic and should be updated as the system's reliability improves over time (Step 10). In the case of the kanban system the number of kanbans effectively determines and controls the size of the SWIP between two processes.

The size of a SWIP buffer is influenced by several factors: the variation of the operation, the response time of the preceding process, withdrawal frequency of the subsequent process, the lot size and the variability in demand. SWIP should be used to ensure the smooth operation of the system but special care must be placed in avoiding using SWIP to cover problems that can be resolved.

2.10 Step 10: Systematically reduce SWIP between cells to reduce variation – improve reliability of machines, operator's work, improve capability of machines & mistake-proof processes.

In the first stages of production, the manufacturing system is expected to encounter some problems and disruptions. These problems arise from several factors like inexperienced workers or unfamiliarity with new technologies and equipment. These problems must be systematically addressed to find the root cause and eventually eliminate them permanently. Furthermore, a great emphasis must be placed in the constant improvement of all aspects of the manufacturing system; from improving machine reliability to facilitating the operator's work to eliminating unnecessary steps. The system's support team must regard this process as a priority. As it was mentioned before, the use of SWIP to hide these problems will only result in recurring disruptions. Which in turn will lead to a further increase in the SWIP bringing all the problems associated with large inventories: long lead times, long throughput, difficulty to find quality problems, etc.

As the process of improvement progresses, the system becomes more stable and production more predictable in terms of time, volume and quality. These improvements enable the system to require less SWIP to protect itself from disruptions. Therefore, the system should be constantly evaluated to adjust the levels of SWIP between processes.

2.11 Step 11: Link Suppliers

The relationship between Original Equipment Manufacturers (OEMs) and their suppliers has traditionally been tense. In their book, "The Machine that Changed the World," Womack, Jones and Roos describe how the American Automotive industry treated their suppliers for most of the century [Womack, Jones and Roos, 1991]. Suppliers were viewed more as competitors rather than as collaborative partners. There was no information sharing between the OEMs and their suppliers, thus the OEM had little or no information concerning the cost structure of the parts. For this reason, the OEM would often request cost reductions that would not reduce the cost of the value stream but rather translated into a reduction of profit margins on the part of the supplier. In this way, the value stream did not become more efficient; it only moved the profits from one player to another.

As an integral part of the value stream, the suppliers can be linked in very much the same way as subsystems within a manufacturing system (Step 9). There are minor differences between the links to suppliers and those within a manufacturing system, namely the time it takes to convey information and material is longer and there are financial transactions associated with these interactions.

The kanban method of pull can be used to link suppliers to the operation of the manufacturing system. The supplier shipment frequency has a great influence on the size of the SWIP required to operate the links. Depending on the location of the supplier and the size of the parts, the shipment frequency can be hourly, daily or weekly. The less frequent the shipments, the more SWIP is needed to run the system. One method of increasing the shipment frequency from suppliers without increasing the transportation costs is to adopt a "milk runs" system where many customers that share a delivery truck or other shipping unit can divide the delivery costs.

2.12 Step 12: Align product development with the linked-cell system of plants

The product development process traditionally precedes the design of the manufacturing system. Usually, the product is designed to conform to a set of requirements and constraints that are gathered from the customer and other sources. Often times, little or no attention is paid to the manufacturability of the product. As organizations recognize the impact of product design in the cost and manufacturability of the product, the design process has become more important. Moreover, special attention is being paid to the interactions between the development of the product and the development of its manufacturing system. It is important to approach both development processes with cross-functional teams in order to make informed decisions.

Cross functional teams are more effective when they operate under a structured environment. Ulrich and Eppinger propose a Design For Manufacturing (DFM) methodology that consists of five steps [Ulrich and Eppinger, 2000]:

1. Estimate the manufacturing costs
2. Reduce the costs of components
3. Reduce the costs of assembly
4. Reduce the costs of supporting production
5. Consider the impact of DFM decisions on other factors.

Figure 2-23 illustrates the iterative nature of the DFM method.

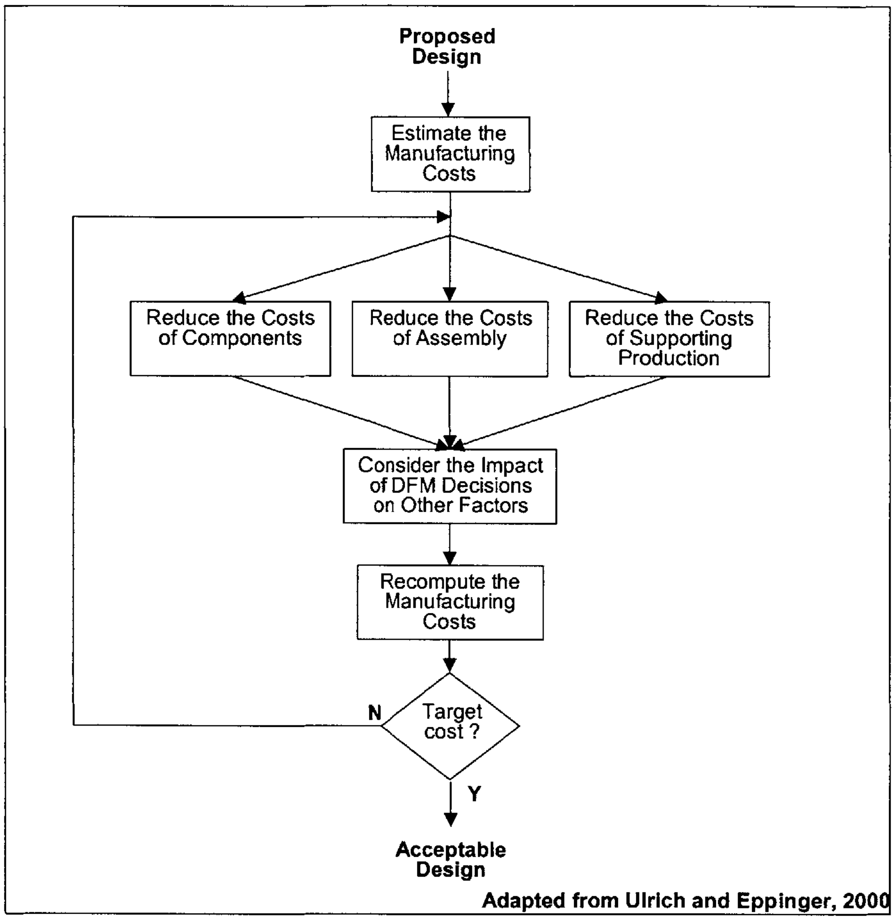


Figure 2-23: The design for Manufacturing (DFM) method

The process displayed in Figure 2-23 has as its primary objective to reduce the manufacturing costs of the product. Therefore, it starts by estimating the costs for the initial proposed design. At this stage, the cost structure is developed in order to identify potential cost reduction areas. In the subsequent steps, these costs are reduced and the resulting design is evaluated. If the cost objectives have not been met, the process is repeated until a satisfactory design is produced.

Chapter 3: Visteon Axle Plant: Designing the Production System for the Rainbow Product

3.1 Introduction

In 1997, Ford Motor Company announced the separation of its automotive components manufacturing division at the Frankfurt Motor Show. The new company was named Visteon and the separation immediately posed new challenges for all its manufacturing facilities. As an independent automotive supplier, Visteon was then forced to compete with other companies for contracts with Ford. On the other hand, it was able conduct business with other automotive Original Equipment Manufacturers (OEM's). In light of the new situation, Visteon recognized the need to improve its production system design in all areas to achieve a significant improvement in cost, quality, responsiveness and delivery.

This work was performed in a manufacturing facility that was established in 1956 to supply Ford Motor Company with axles for all its vehicles, ranging from passenger cars to the largest trucks offered by the automotive company. The plant fabricates the gears and other components for these axles and assembles them into a finished drive axle module. The module is then directly shipped to the vehicle assembly plants. Figure 3-1 shows an exploded assembly view of a typical rear axle. This plant is unusually large in size; for a considerable period of time the plant was the sole supplier of differentials for the American markets. Currently, the 2.8 million square feet factory is capable of shipping 3.8 million axles each year, which makes it the largest manufacturing plant within Visteon.

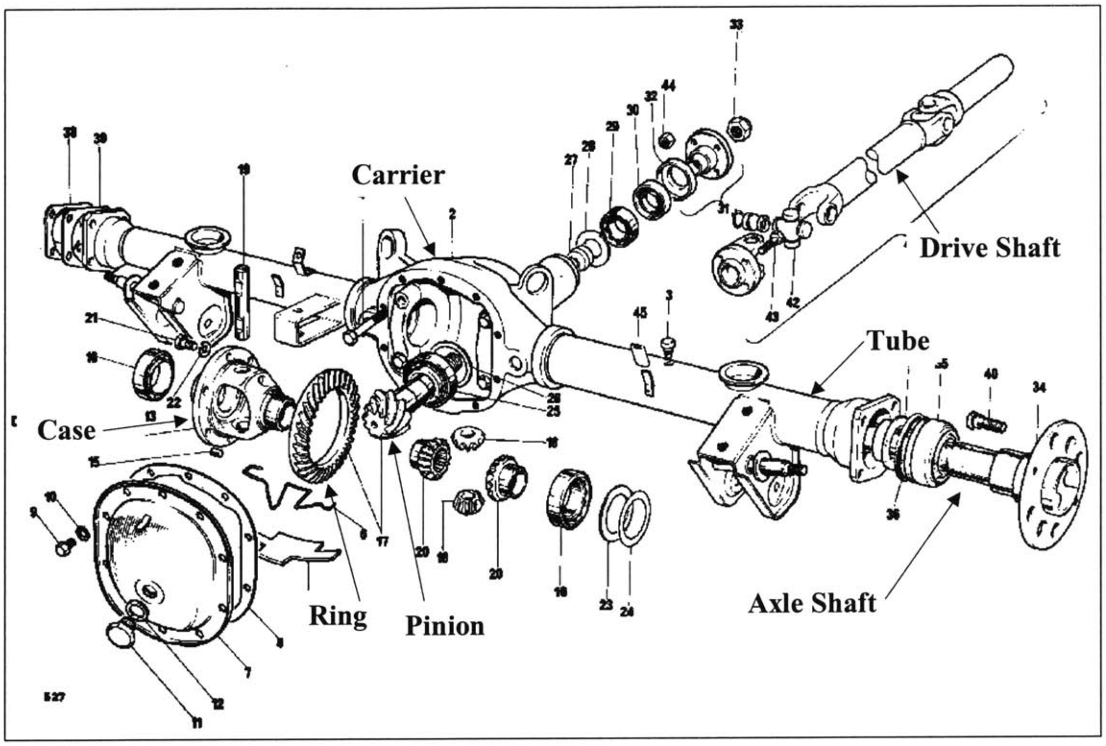


Figure 3-1: Rear axle assembly

At this facility, throughput times are unnecessarily long and unpredictable because of the departmental layout in place. The typical part takes 20 days to be processed from dock to dock and the number of defective parts can be as high as 2.3 out of every 100 units. Figure 3-2 illustrates the enormous complexity present in this plant.

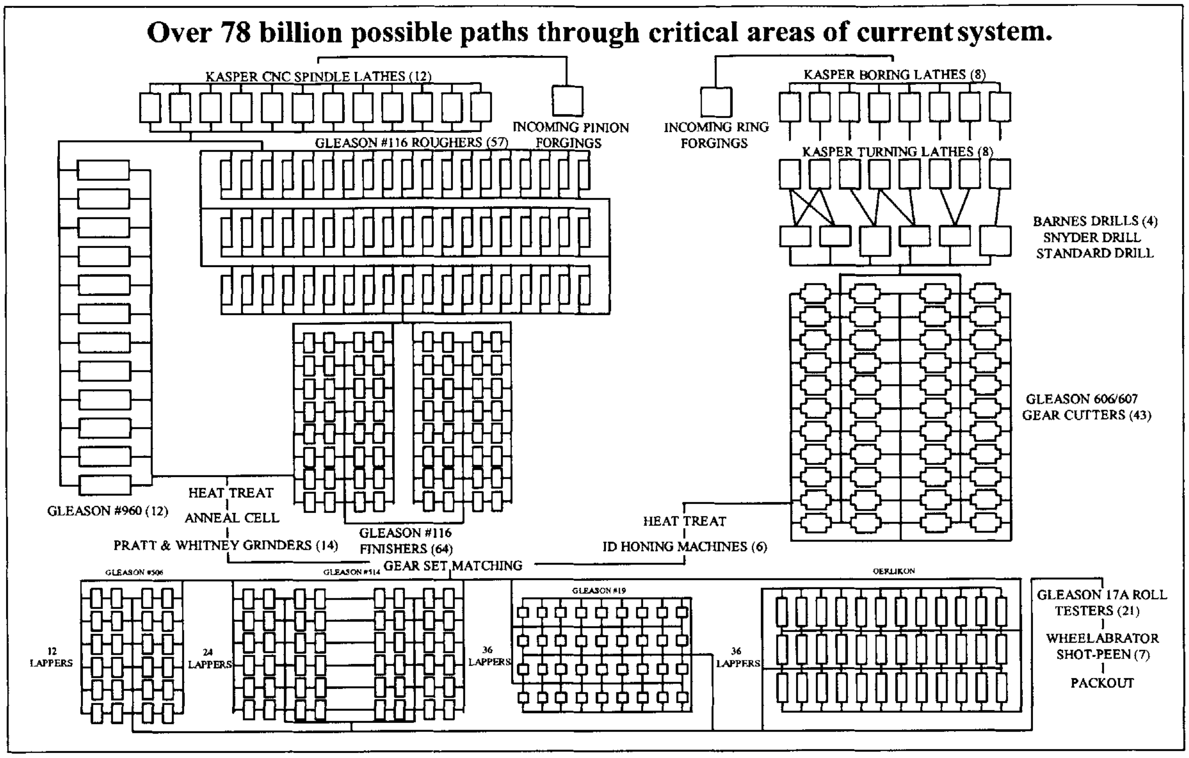


Figure 3-2: Complexity caused by the layout

The characteristics of this factory make it an ideal candidate for improvement. Its age and size however, represent an obstacle to the short-term evolution of the entire facility to become a more effective production system. Nevertheless, the introduction of new products that can justify the investment of new equipment represent excellent opportunities for the design of better production systems planned around a customer or group of customers. Such is the case of a new rear differential assembly that will be supplied to one of the big three automotive manufacturers in the United States. This product was internally named "Rainbow" and this identifier will be utilized to refer to it throughout this document.

This work presents the application of the 12 steps described in Chapter 4 to the design of the production system for the Rainbow product. It describes the current state as well as the steps that must be taken from now until the system reaches full production in May 2001.

3.2 Product Overview: Rainbow

The Rainbow product consists of a rear differential for a new automobile, which will feature an all-wheel drive system. The vehicle is expected to be introduced to the market in early 2002. The Rainbow differential is shipped to a first-tier supplier as a sub-assembly, which in turn will be delivered as a completed axle to the OEM assembly plant. Figure 3-3 shows an illustration of the Rainbow rear differential.

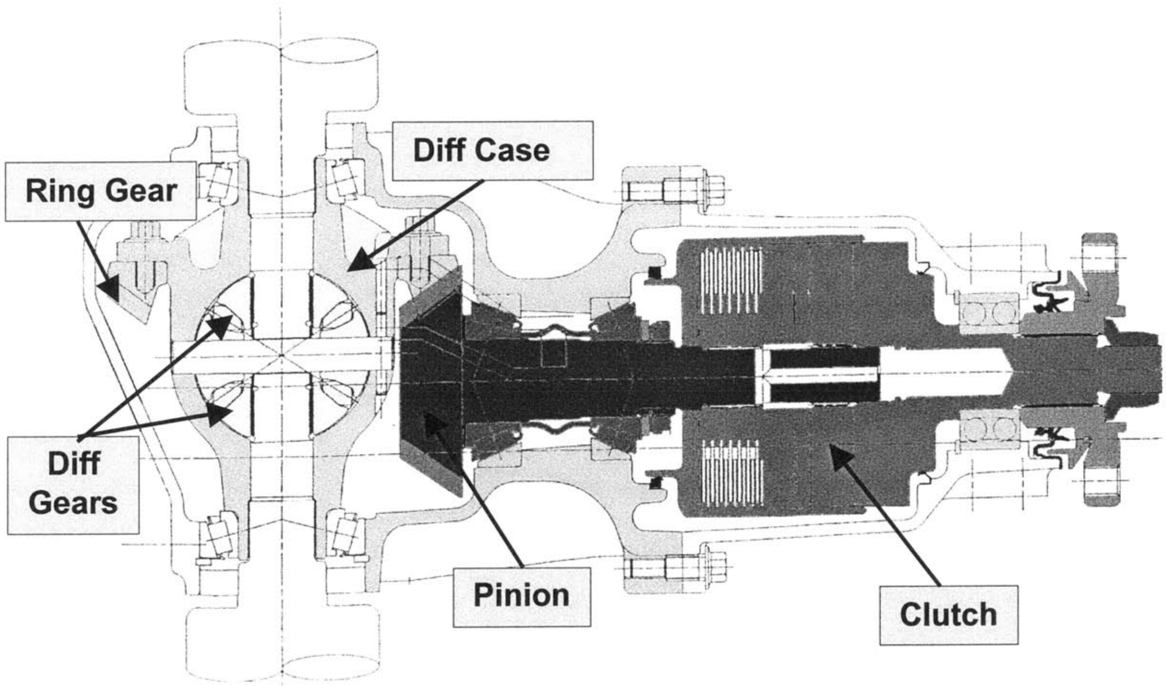


Figure 3-3: The Rainbow rear differential

The Rainbow assembly is conformed by several parts ranging from hypoidial gears to simple nuts and bolts. The plant manufactures the most prominent parts: the *differential case* and the *hypodial ring and pinion gears*. These components are shown in Figure 3-4. The remaining components are purchased from outside suppliers to assemble the complete rear differential.

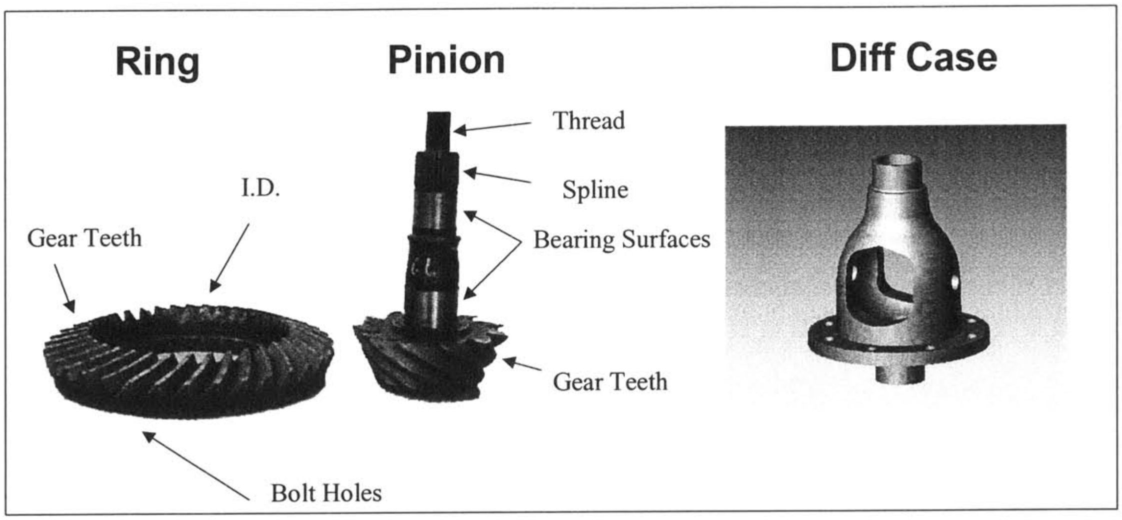


Figure 3-4: Rainbow components manufactured in-house

The process plan to produce the parts is as follows. The gears are machined in two stages termed *green-end* and *hard-end*. At the *green-end* stage, the gear forgings are in a "soft" state and are easier to machine. While in this state, the gears are turned very close to their final dimensions, machined to create features like holes and chamfers and finally, the gear teeth are cut (see Figure 3-5). The business-planning department made the decision early in the project to outsource all of the *green-end* operations except for gear cutting, which is performed in-house. It is worth noting that this type of decision limits the design potential because it is obviously based on a process unit cost calculation (see equation 4) as opposed to looking at the total supply chain management cost.

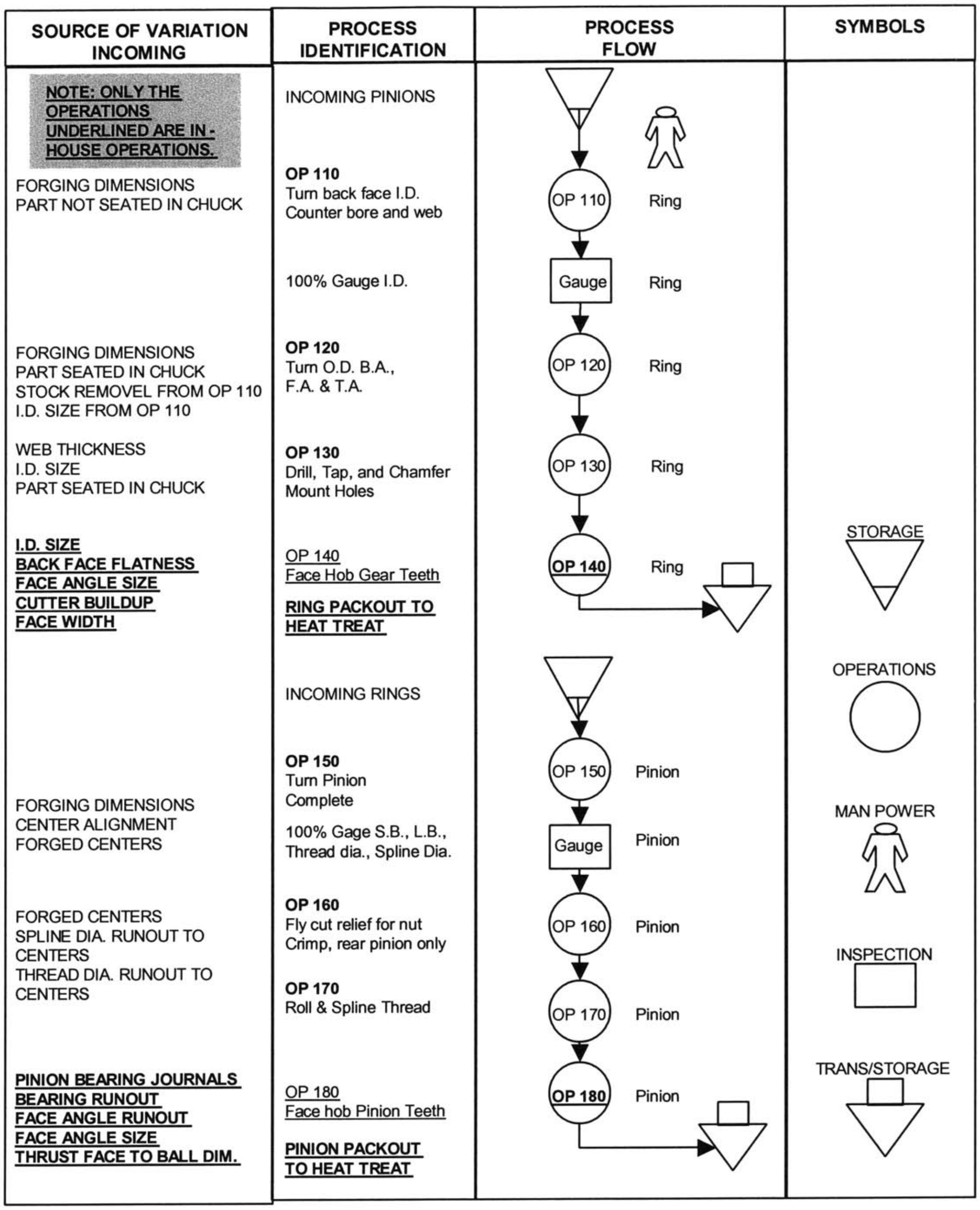


Figure 3-5: Green-End Process Plan

After the *green-end* operation, the gears must be exposed to a carburizing process with the purpose of achieving a particular desired material hardness. It was also decided to outsource this operation to an outside supplier because the necessary capacity was not available at the plant. Once the gears return from the hardening operation they are processed in the *hard-end* cell (see Figure 3-6), where they go through an annealing process and then they must go through a straightening operation to correct any changes in dimension. Additionally, a ring and pinion pair (called a gear set) is lapped to ensure a correct match between their teeth. From this point forward, the ring and pinion become a matched set and must stay together for the rest of the operations in the value stream. Next, the gear pair is submitted to a shot-peen operation to achieve a particular surface hardness and finally, the parts flow through a chemical process to reduce the wear in the early stages of the product life.

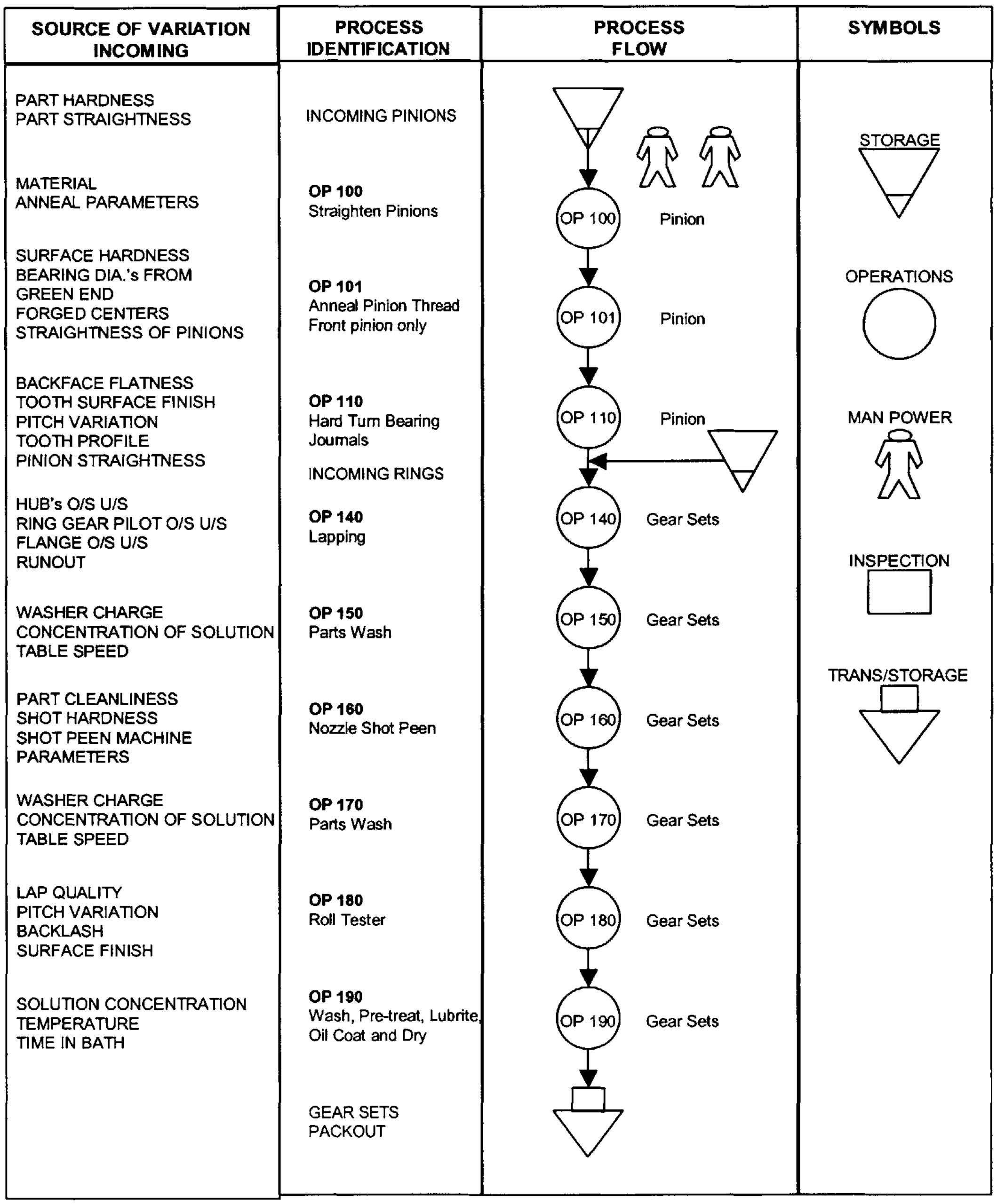


Figure 3-6: Hard-end Cell Process Plan

Another part of the axle that will be fabricated in the plant is the differential gear case. The manufacturing process for this component consists mainly of machining operations (see Figure 3-7). The case casting is machined by different individual stations to create features like holes and critical surfaces. Finally, the case is washed and assembled with other supplied parts.

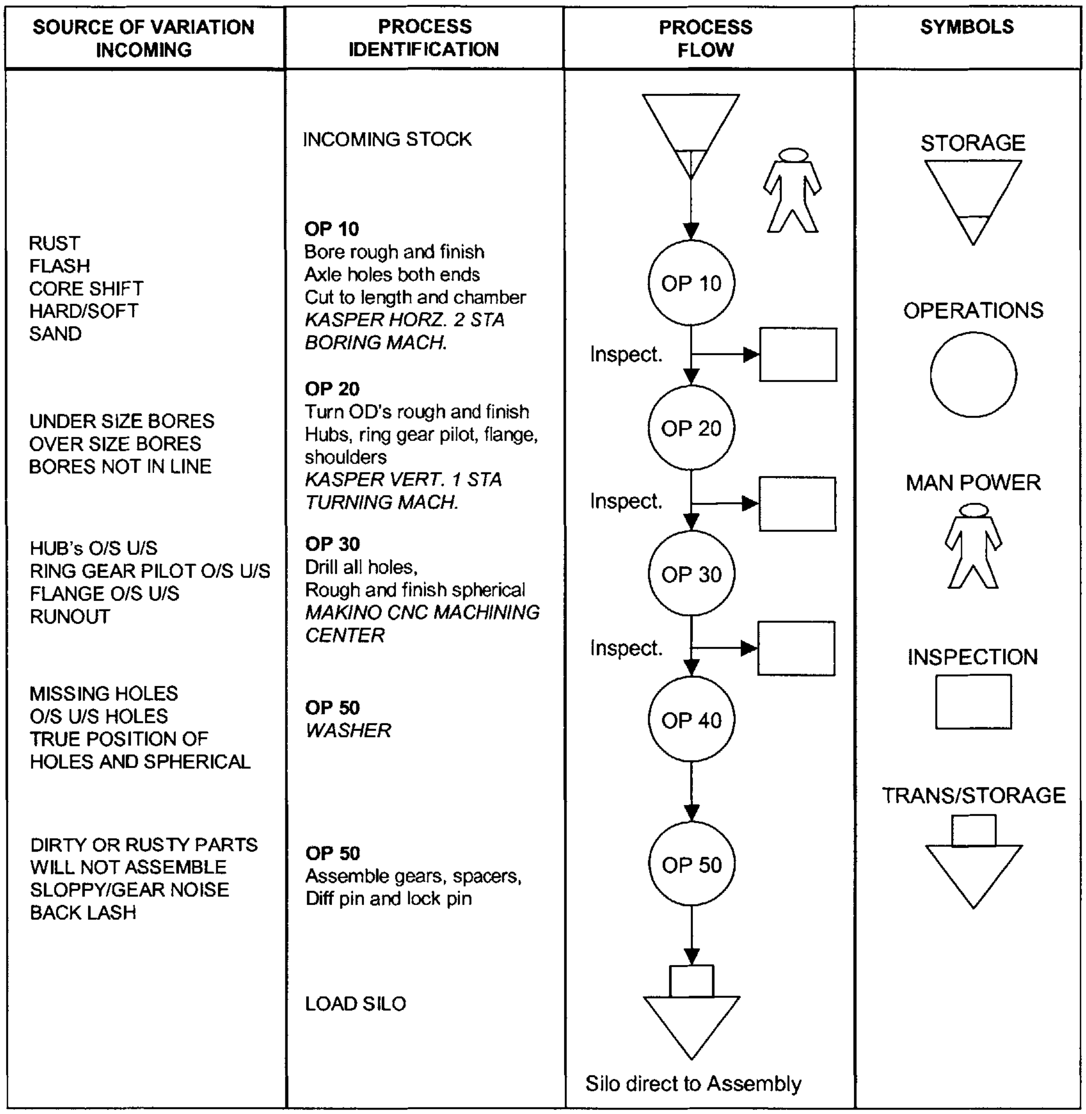


Figure 3-7: Differential Gear Case Cell Process Plan

3.3 Designing the Production System for Rainbow

3.3.1 Steps 1 &2: Forming a common mental model and developing clear objectives

The first step in designing the production system for Rainbow was to make sure everyone in the design team understood the objectives of the project. The MSDD was used as the basis to understand how the particular decisions and implementations at the shop floor level impacted the overall goals of the system. This goal was achieved through several seminars and numerous discussions in which the entire design team participated as a group. In this way, it was intended to create a clear picture for everyone in the design team of the scope and objectives of the project.

3.3.2 Step 3: Identifying the customer and planning the capacity

In this particular case, identifying the customer is a simple task. There is only one product with no variations and it will be supplied to a single customer. There are no product families or customers to group.

Additionally, the demand volume is expected to be 80,000 units per year. This demand is predicted to stay fairly constant throughout the product life experimenting only slight temporary variations. For practical purposes, it is assumed that variation in demand will not be greater than 10% in either direction. With this information, the system was designed to achieve a maximum yearly capacity of 88,000 units. In the event of a decrease in demand, the system design (because of man-machine separation) is robust enough to be able to adapt to smaller production volumes.

3.3.3 Step 4: Defining takt time

To calculate the system takt time it is assumed that there are only 7.2 effective working hours in an eight-hour shift due to scheduled breaks. Also, there are five working days in each week and only 47 effective weeks in a year. Therefore the total available time each year is 1692 hours per shift. Table 3-1 shows the takt times for the expected range of yearly demand according to the number of daily shifts scheduled. The takt time calculations include a 15% allowance for unscheduled downtime.

Table 3-1: Takt times for the range of expected demand

	Takt Time		
Demand Units/year	**72,000**	**80,000**	**88,000** (Min Takt time)
Number of shifts			
1	71.9 sec	64.7 sec	58.8 sec
2	143.8 sec	129.4 sec	117.6 sec
3	215.7 sec	194.1 sec	176.5 sec

3.3.4 Step 5: Defining production flow

At this stage, the interest is at the system level; therefore the amount of detail chosen for the production flow diagrams is limited. The scope of the value stream will encompass the material and information flow within the plant as well as the similar exchanges between the plant and both its first tier supplier and its immediate customer.

There are two clearly distinguishable production flows for the rainbow product: the value stream for the differential case and the value stream for the gears. The first value stream is simple because it consists of only two processes: the differential case machining operation and final assembly. Figure 3-8 shows the value stream map for this production flow. The initiation point for production in this flow is located at the staging area. The information conveyed to this area consists of an electronic shipping order with information regarding the quantity of products to be shipped (again, there is only one product type). This information is created based on the customer requirements in the form of supplier kanbans (electronic). The staging area pulls the required product from the SWIP buffer after final assembly and ships it. This action triggers a production ordering kanban to be released to the assembly cell in order to replenish the withdrawn goods. The assembly cell then pulls the required differential gear case (and the rest of the required materials) in order to complete the production order. This pull generates another kanban loop in which the differential case cell produces to replenish the min-max buffer between this cell and assembly when the minimum level is reached. This cell also pulls the necessary materials from standard inventory, which sends a signal kanban to the production control unit in order to replenish the materials used. The production control unit uses this information to generate supplier kanbans that are sent to the suppliers through another kanban loop. In this way, production is only scheduled at one point and the system responds to these changes producing what is needed when it is needed.

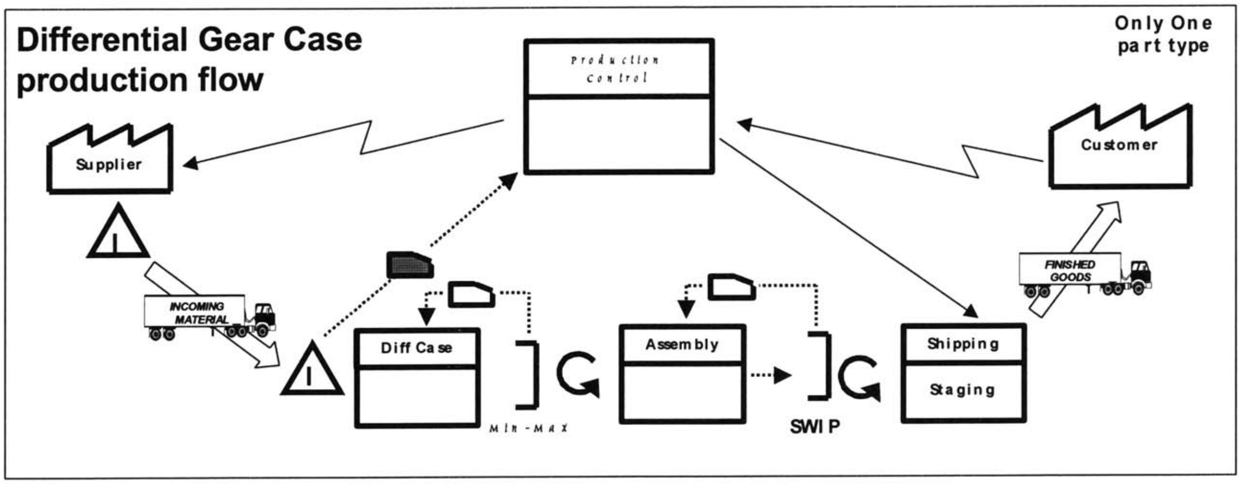


Figure 3-8: Differential case value stream map

The production flow for the gears is slightly more complicated. The process for the gears includes four operations: green-end machining, heat treat, hard end machining and final assembly. Since the heat treat operation is outsourced it could be viewed as an intermediary customer, but the gears are directly sent back to plant after the temperature hardening operation. Therefore, the heat treat process will be treated as if it were located within the plant. The only difference is that there exists a delay in the information and material transfer to and from heat treat. Figure 3-9 illustrates the value stream for the gears.

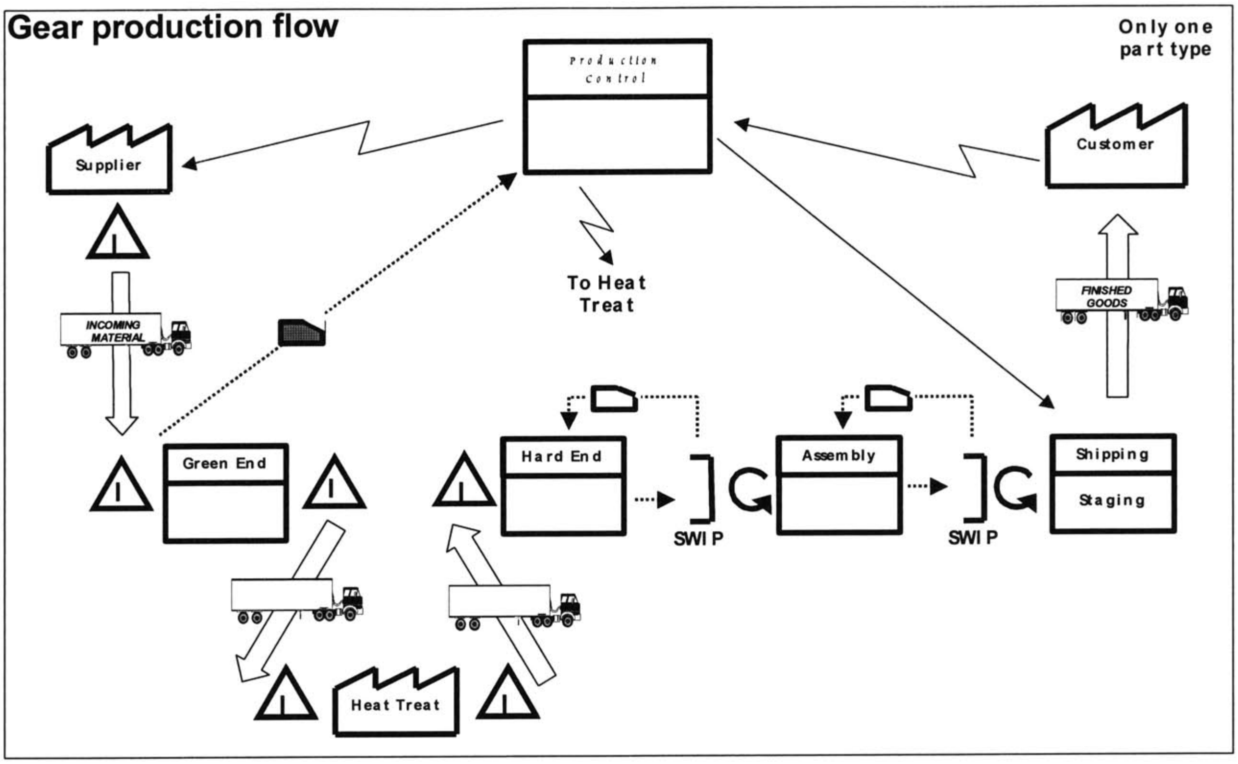


Figure 3-9: Gear production value stream map

This value stream for the gears operates in the same manner as the differential gear case value stream. It is a pull system with the scheduling point at the end of the stream (last point inside the plant). The product necessary for shipping is pulled from a SWIP unit and that triggers a production kanban in order to replenish the goods. The preceding cell (assembly) pulls the necessary materials from another SWIP unit and the process continues upstream. The only difference in this flow is the heat treat operation, which introduces a delay in the material and information transfer between the plant and the supplier.

3.3.5 Step 6: Forming cells

The Rainbow rear differential differs in a few aspects from the conventional product manufactured at this plant. The most important of these differences is the size of the Rainbow components, which are significantly smaller than the usual product fabricated at this plant. For example, a conventional ring weighs approximately 20 lb whereas the rainbow ring weighs a only 5 lb. The size of the rainbow parts makes it easier for the operators to move the parts manually from station to station. For this reason, manual transfer of parts with single piece flow requires no material transport devices to assist the operators. As it was shown in Table 3-1 the demand volume leads to takt times greater than 30 seconds.

The operating pattern for a cell is ideally two daily shifts with time in between to perform maintenance and other support tasks. The Rainbow cells however were under certain constraints. First, the initial estimates for the quantity to be demanded based on the customer plan considered a scenario where the demand would be approximately 120,000 parts per year, almost 50% more than the actual demand. Several decisions including the selection of equipment were made to ensure that the higher demand could be met. Additionally, the business policy of the company, which is enforced differently in each department, drives people to run the equipment 3 shifts. This investment model does account for the fact that a system might never achieve the right quantity or right mix. Furthermore, the cell design is done under the supervision of management from different functional departments. This places different constraints on each design team and the final result was an unbalanced system in which each cells are run with different operating patterns. The differential case will be operating three 8-hour shifts per day for five days a week with an additional 10-hour shift on Saturdays. The gear cells (green-end and hard-end) will be operating two shifts per day during five days each week. And finally, the assembly cell will operate only one shift per day also during five days each week.

The imbalance in the operating pattern between areas resulted in the need for larger SWIP buffers between processes as will be seen in step 9. The resulting takt times for each cell are displayed in Table 3-2.

Table 3-2: Takt times for the Rainbow cells

Cell	Takt Time (sec)
Differential Case	214
Green-end	130
Hard-end	130
Assembly	65

3.3.5.1 Equipment Selection

The guidelines for the selection of the equipment presented in Chapter 2 were followed when designing the Rainbow cells. Here are some examples of what was done to ensure the equipment was well suited for cellular manufacturing.

Breaking up an operation to balance the differential case cell and reduce the walking distance:

The first two operations of the differential case fabrication cell were originally planned to be performed by a single machine with two spindles arranged horizontally. The advantage of this machine was that it required the part to be located only once. On the other hand, the horizontal configuration resulted in a piece of equipment that was unnecessarily long and increased the walking distance of the operator considerably.

After exploring other alternatives, it was decided to divide the operation into two machines with a vertical configuration. The result was a more compact design that reduced the walking distance of the operator by 3ft even after adding a gauging station in between the machines. Additionally, the new machines are simpler and easier to service and their more general design facilitates reusing them for other purposes in the future. Figure 3-10 shows a schematic representation of these operations.

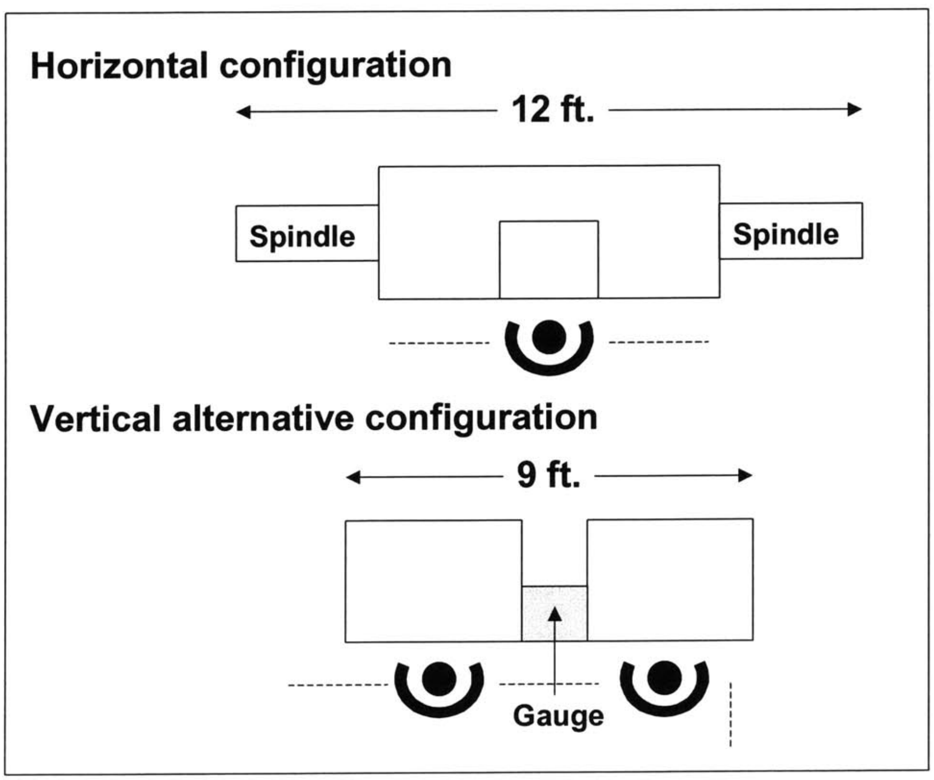


Figure 3-10: Operation break-up to reduce walking distance

New technologies to enable takt time oriented equipment

The traditional technology used to shot peen parts assumes it will be continuously operated and supervised by one operator. Therefore, it was designed to have a fast cycle time to keep the operator busy. A rotary dial machine is used to subdivide the process cycle to meet the desired cycle time. This requires a high level WIP within the machine to achieve the volume needed. The resulting machine is highly complex and has poor reliability because of the increased number of moving parts.

In order to integrate the shot peen operation into the gear cell to maintain the minimum takt time to achieve continuous flow, it was necessary to use a different technology. The new technology is capable of performing the shot peen operation in 27 seconds, well below the expected takt time of 130 seconds. Furthermore, it does it one piece at a time, which aids in maintaining single piece flow and eliminates the large quantities of WIP needed with the previous technology.

Ergonomic working heights

The equipment for all four cells was chosen with ergonomic principles in mind. An important ergonomic characteristic is the working height, especially with relatively heavy parts. The machines were chosen to have a working height of no less than 3 ft. and no more than 4.5 ft. Furthermore, within each individual cell, emphasis was placed to maintain a constant working height. The differential case cell, for example, utilizes machines that have different working heights by design (again the choice of machines was influenced by business policy and right-sized machines not being available from suppliers). Therefore, the machines were installed on specially designed bases so that the working height was constant throughout the work loop. Additionally, in order avoid making permanent modifications to the floor like installation pits for tall machines; a platform was needed to bring the operator to the proper height. Figure 3-11 illustrates this configuration. It is worth mentioning that it would have been better to use machines designed to have an ergonomic working height, but given the circumstances this solution was adopted to meet the requirements of the system.

Figure 3-11: Differential Case Cell

3.3.5.2 Layout Design

The layout of the cells was designed with the objective of minimizing the walking distance for the operators. Also, the environment created by the layout was considered. All the cells consist of two parallel rows of equipment. Figure 3-12 shows the layout for the Differential Case cell. In this cell, the material is transported by the operator without the need for a conveyor or material movement assisting device.

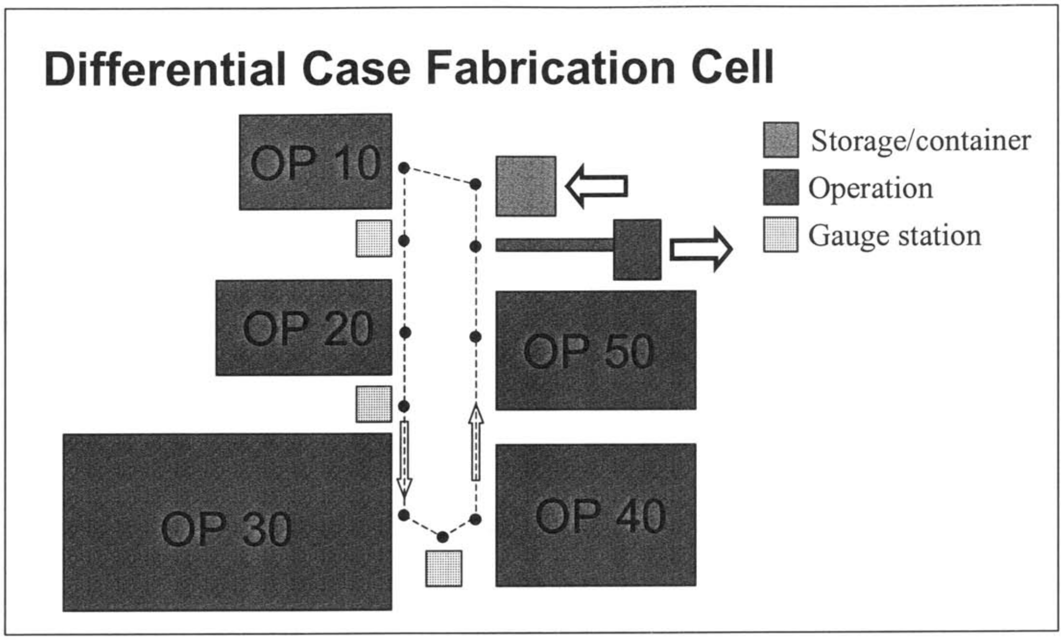


Figure 3-12: Differential Case Cell Layout

The green-end gear cell layout is displayed in Figure 3-13. In this cell, there is also no need for a conveyor and all parts are moved manually.

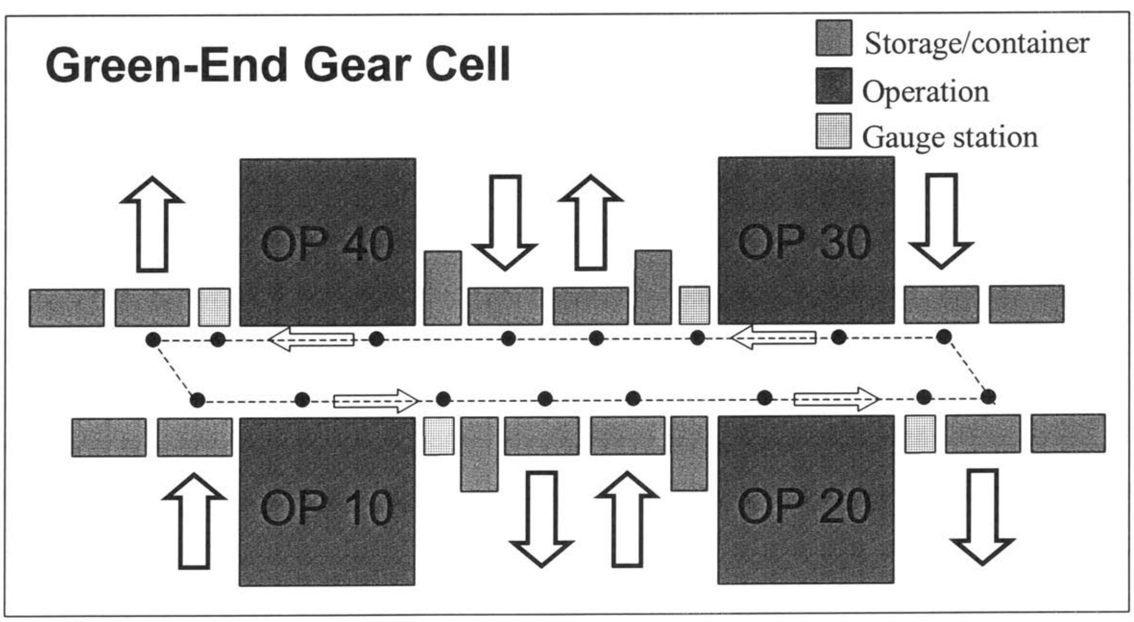


Figure 3-13: Green-End Gear Cell Layout

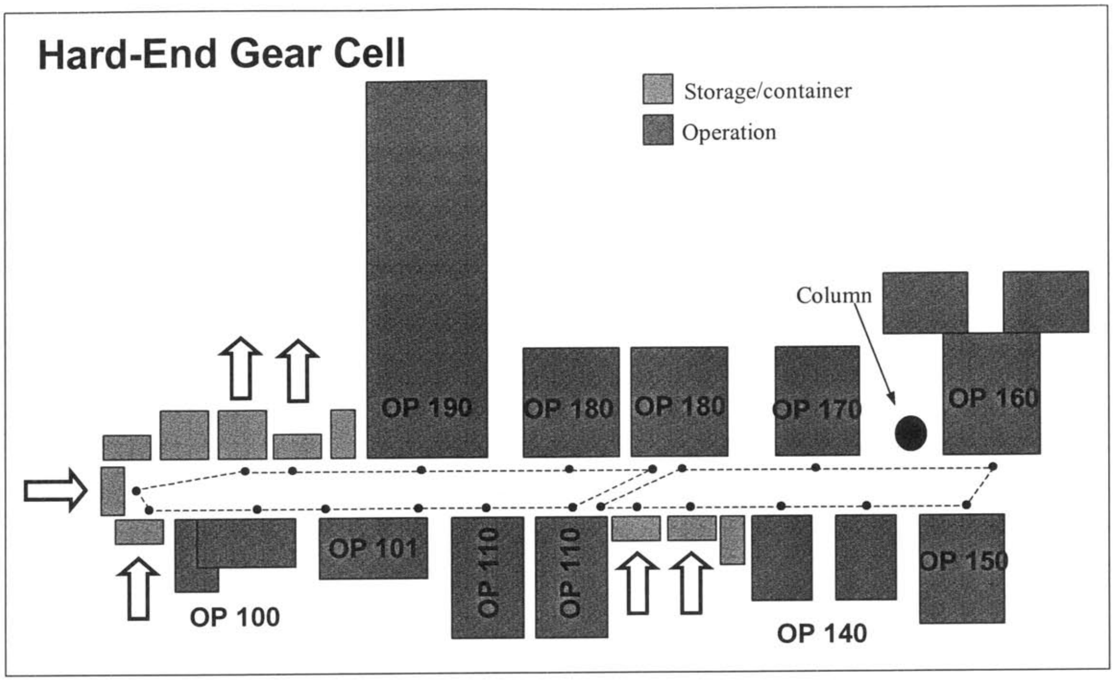


Figure 3-14: Hard-end Gear Cell Layout

The hard-end cell layout is shown in Figure 3-14. In this case, because of the number of parts being carried from station to station (see standardized work sheet on next section), an overhead rail system was used. The rail supports a rack that can hold up to 4 sets of parts (ring and pinion). Figure 3-15 shows the rail system. Note that the machine that performs operation 160 (shot peen) is has a design that increases the walking distance of the operator. The machine could have been re-designed to reduce the wasted space in between operation 170 and operation 160. However, it was decided not to waste any resources in the re-design of this machine because a structural column that sits in between this machine and operation 170 would have prevented any reduction in the length of the cell.

Finally, the assembly cell layout is shown in Figure 3-16. In this case, the large quantity of parts and their size made it necessary to utilize a pallet and conveyor system. The use of the conveyor determined to some extent the layout of this cell. Some of the parts have to be pressed onto the differential carrier. In order to keep the conveyor simple and inexpensive, it was decided that these pressing operations would be done before the part is placed on the pallet. This caused a departure from the open-ended parallel rows of equipment design as can be seen in Figure 3-16.

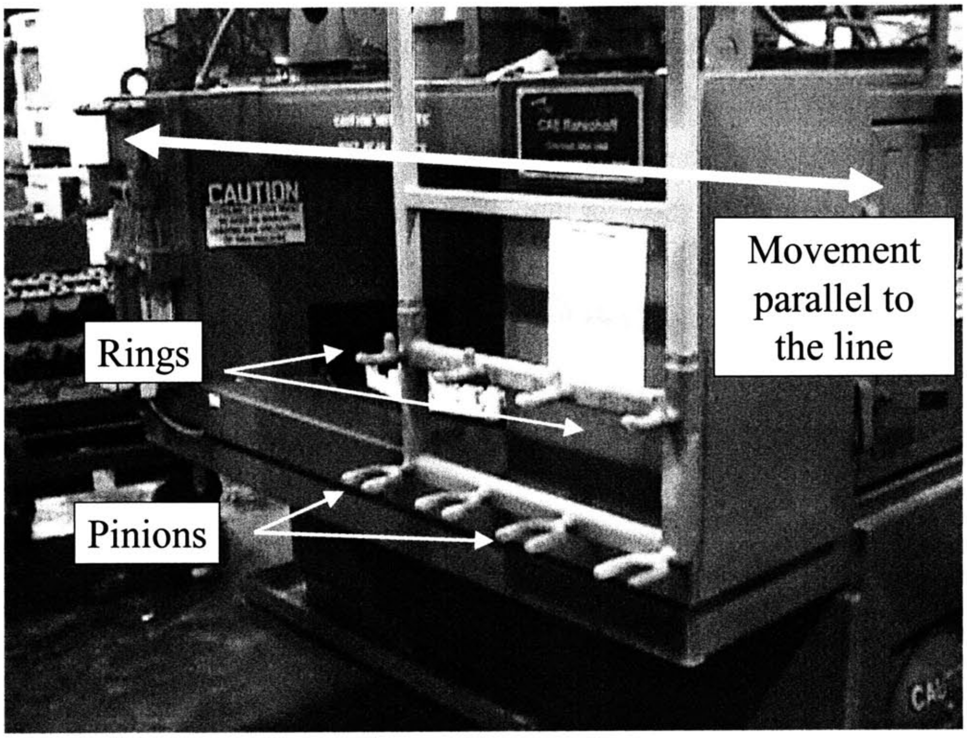


Figure 3-15: Rack to help carry the parts

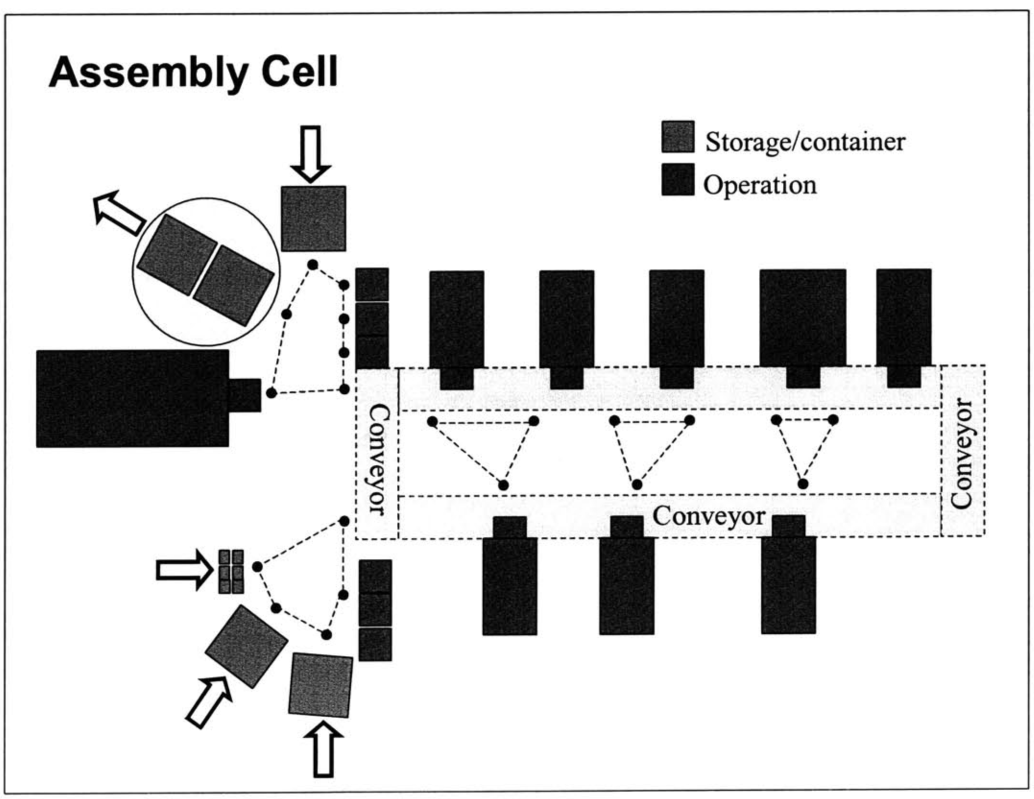


Figure 3-16: Assembly Cell Layout

3.3.5.3 Standardized Work Methods

Once the layouts have been designed, the work methods were defined and balanced. A standardized work combination sheet was created for each operator in each cell. For the expected volume of approximately 80,000 parts, a single worker will operate the differential case cell. The standardized work combination sheet for this cell is shown in Figure 3-17. Figure 3-18 shows the standardized work combination sheet for the operation of the green-end cell with one operator. For the same volume, the hard-end cell will be run with two operators. Figure 3-20 shows the standardized work methods for both operators. Finally, five operators will staff the assembly cell. The standardized work combination sheet for all five operators is shown in Figure 3-19.

PART: 1

PROCESS		TIME			
OP#	OPERATION	Man	Walk	Auto	Wait
0	Pick up (1) part from bin	3	1.3	0.0	0
10	Load/Unload (1) part in op 10	5	2.7	112.0	0
10	Gauge op 10 part every 5th cycle	6	2.7	0.0	0
20	Load/Unload (1) part in op 20	5	2.7	117.0	0
20	Gauge op 20 part every 5th cycle	6	4.0	0.0	0
30	Set parts on semi finish part op 3	1	0.0	0.0	0
30	Unload op 30 B Load and set on	4	0.0	0.0	0
30	Transfer (2) parts from op 30 A lo	4	0.0	214.0	111
30	Load (2) parts onto op 30 A load	4	0.0	214.0	0
30	Pick up (1) part from finish op 30	1	1.3	0.0	0
30	Gauge op 30 part every 5th cycle	6	1.3	0.0	0
40	Load/Unload (1) part in op 40	5	6.7	120.0	0
50	Pick up (2) large gears and butte	3	0.0	0.0	0
50	Pick up (2) small gears and butte	3	0.0	0.0	0
50	Pick up (2) large washers and pla	3	0.0	0.0	0.0
50	Pick up (2) small washers and pl	3	0.0	0.0	0.0
50	Assemble diff case	15	3.0	0.0	0.0
0	place (2) parts on elevator to silo	2	2.3	0.0	0

Operator 1 Loop Time: 218. sec.

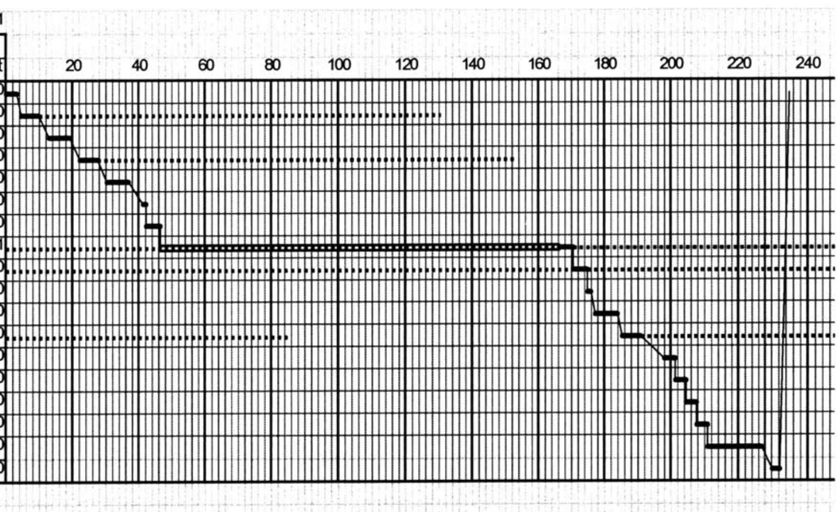


Figure 3-17: Standardized Work Combination Sheet for the Differential Case Cell

PART: 1

PROCESS		TIME			
OP#	OPERATION	Man	Walk	Auto	Wait
10	Pick up a front ring from container	2	3.0	0.0	0
10	Unload and reload op 10, start cycle	5	2.7	120.0	27
10	gage op 10 every fifth cycle	6	1.7	0.0	0
10	set front ring on packout dunnage	3	1.7	0.0	0
20	Pick up a rear pinion from container	2	2.3	0.0	0
20	Unload and reload op 20, start cycle	5	1.7	120.0	0
20	gage op 20 every fifth cycle	6	2.7	0.0	0
20	set rear pinion on packout dunnage	3	1.7	0.0	0
30	Pick up a rear ring from container	2	3.0	0.0	0
30	Unload and reload op 30, start cycle	5	2.0	120.0	0
30	gage op 30 every fifth cycle	6	1.7	0.0	0
30	set rear ring on packout dunnage	3	1.3	0.0	0
40	Pick up a front pinion from container	2	2.7	0.0	0
40	Unload and reload op 40, start cycle	5	1.7	120.0	0
40	gage op 40 every fifth cycle	6	2.3	0.0	0.0
40	set front pinion on packout dunnage	3	2.0	0.0	0.0
	Operator 1 Loop Time: 125. sec.				

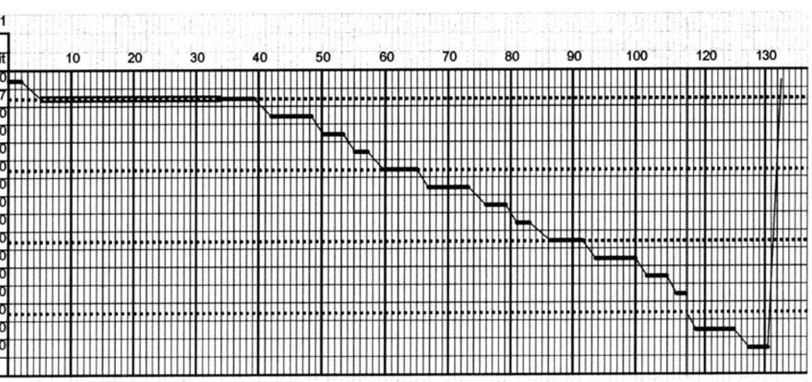


Figure 3-18: Standardized Work Combination Sheet for the Green-End cell

PART:

PROCESS		TIME			
OP#	OPERATION	Man	Walk	Auto	Wait
150	Load Diff Case & ring gear to fix	10	0.0	0.0	0
150	Start Cycle	1	1.3	0.0	0
150	Load Cones, Upper & Lower	6	0.0	22.0	0
150	Load Diff to Cone press	4	0.0	30.0	0
150	Start Cycle	1	1.0	30.0	0
150	Load diff to torque bolts	4	0.0	35.0	0
150	Place and start bolts	8	0.0	30.0	0
150	Start Cycle	1	1.0	30.0	0
150	Load diff assy & pinion to pallet	5	0.0	30.0	0
150	Unload Pto to test stand	7	0.0	30.0	0
150	Unload Pto to dunnage	8	1.3	30.0	0
150	Install hose	8	0.0		0
	Operator 1 Loop Time: 67.7 sec.				
10	Load Carrier & Cover to fixture; L	15	0.0		0.0
10	Start cycle	1	1.3	15.0	0.0
10	Press cycle	6	0.0		0.0
10	Load clutch to pallet	7	0.0		0.0
10	Load Carrier to press fixture	6	0.0		0.0
10	Load Cover to S/R press fixture	6	0.0		0.0
10	Start cycle	1	1.0	25.0	0.0
10	Press cycle	6	2.3		0.0
10	Load Housing cover to pallet	8	0.0		0.0
10	Load Cover to pallet	8	0.0		0.0
	Operator 2 Loop Time: 68.7 sec.				
140	Tech to invert housing	8	0.0		0.0
140	Place Axle tube seals	8	0.0		0.0
140	Start cycle	1	1.3	20.0	0.0
60	Place fr. cover to housing	6	0.0		0.0
60	Place & start (6) bolts	10	0.0		0.0
60	Start cycle	1	1.7	10.0	0.0
20	Place pinion cone in housing	4	0.0		0.0
20	Start cycle	1	1.7	30.0	0.0
20	Select/verify shim	10	0.0		0.0
20	Install shim over pinion	4	0.0		0.0
20	Remove pinion cone from housi	4	0.0		0.0
20	Place cone to pinion	4	0.0		0.0
20	Start cycle	1	1.3	25.0	0.0
	Operator 3 Loop Time: 68. sec.				
110	Place and start (8) bolts	15	0.0		0.0
110	Start cycle	1	2.0	15.0	0.0
100	Place R. cover to tooling	12	0.0	0.0	0.0
100	Start cycle	1	1.0	19.0	0.0
30	Invert housing over pinion	8	0.0		0.0
30	Install collapsable spacer	4	3.0		0.0
30	Place cone to pinion	5	0.0		0.0
30	Place pinion nut	4	0.0		0.0
30	Place flange	5	0.0		0.0
30	Place flange nut	4	0.0		0.0
	Operator 4 Loop Time: 65. sec.				
80	Inspect pattern ck. Backlash	24	0		0
80	Release pallet	1	2		0
70	Remove master shims	8	0		0
70	Replace/actual shims&cups	15	1		0
50	Invert housing and place	5	0		0
50	Place diff/master shims	11	1		0
	Operator 5 Loop Time: 68. sec.				

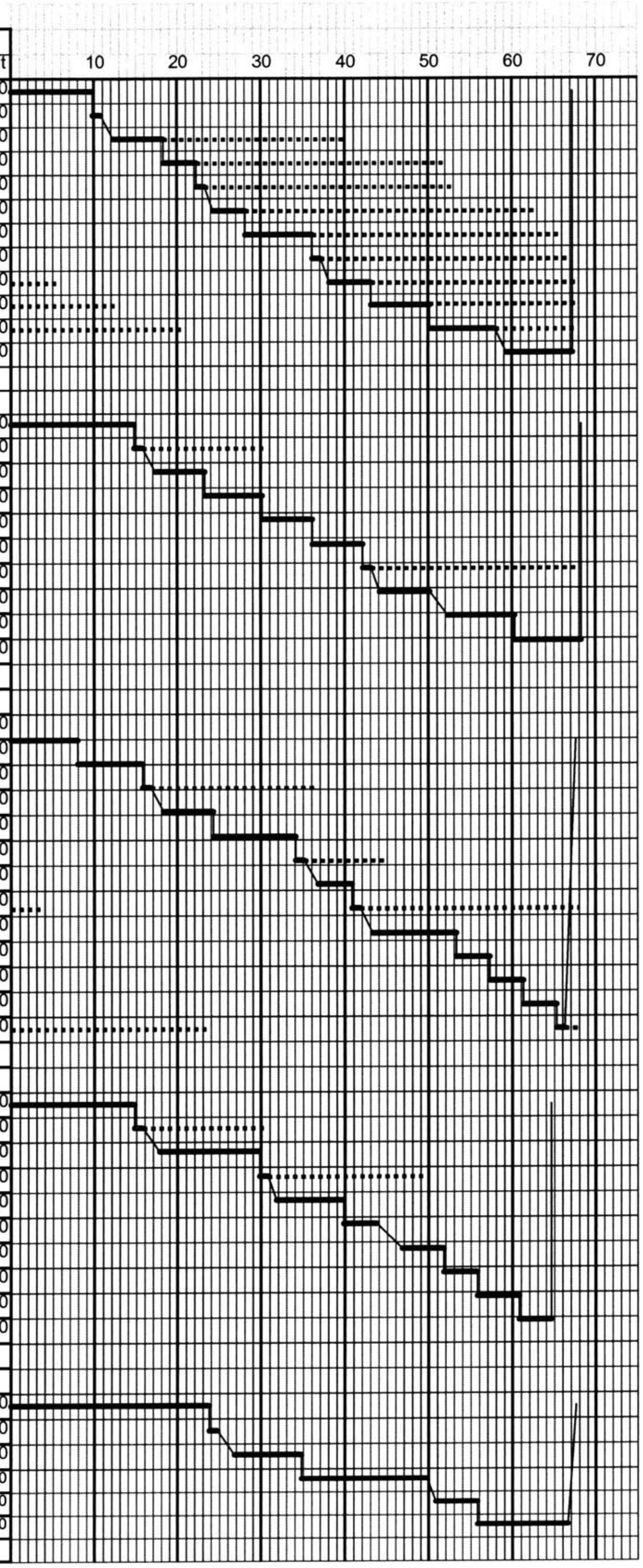


Figure 3-19: Standardized Work Combination Sheet for the Assembly cell

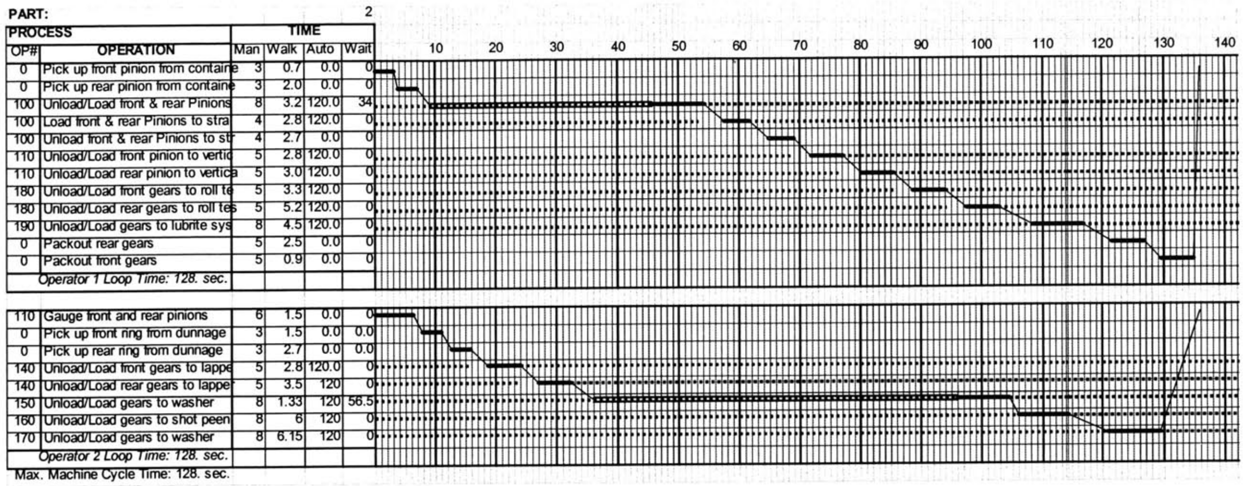


Figure 3-20: Standardized Work Combination Sheet for the Hard-End Cell

The standardized work combination sheets are a great design tool but are not very effective in communicating the work methods to the operators. Appendix C shows the work instructions for the Differential Case cell worker. Similar instructions must be developed before the system is operational to guarantee that the work methods will be followed.

3.3.6 Step 7 & 8: Reducing setup times and Leveling production

In this case, since there is only one product type, this step does not include changeovers. It considers, however, the time it takes to initially setup a machine at the beginning of each shift or the time lost due to tool changes. As the support teams familiarize with the equipment, the techniques used to setup the machines must be improved.

Again, this system will produce only one part type; therefore it is not necessary to level production. In the future, if new product models are added to the system, it will be necessary to use a Heijunka box or other similar leveling technique.

3.3.7 Step 9 & 10: Operating the linked system

The difference in the operating pattern between the cells calls for a larger SWIP buffer in between them. The differential gear case cell will be operated for three shifts each day but the assembly cell will only be running for one shift. This means that the assembly cell will consume in one shift three times the production capacity of the differential gear case cell. In order to avoid the starvation of the assembly cell, the SWIP buffer in between the two cells must contain a minimum of two shifts worth of production of the upstream cell (roughly 220 parts) at the beginning of the assembly shift. In addition to this required buffer, the system should also account for any unscheduled disruptions that might occur in the daily operations. Therefore, the maximum level of SWIP in between these two cells must be 220 parts plus the desired safety factor.

The hard-end cell is also run at a different operating pattern than the assembly cell. The hard-end cell will be run two shifts daily, which means that the buffer between this cell and the assembly unit must contain a minimum of one shift worth of the hard-end cell production (roughly 165 parts). Again, a safety factor should be considered to protect the system from unexpected interruptions.

Once the system is running, and it is continuously improved, the system will become more stable and production more predictable in terms of time, volume and quality. These improvements will enable the system to require less SWIP to protect itself from disruptions. Therefore, the system should be constantly evaluated to adjust the safety factor and improve the levels of SWIP between processes.

3.3.8 Step 11: Linking suppliers

As an integral part of the value stream, the suppliers must be linked in very much the same way as subsystems within a manufacturing system (Step 9). Most suppliers for Rainbow already have an electronic link to this plant. This facilitates the transfer of information to establish a real pull system. Also, a significant number of suppliers deliver parts to other production processes within Visteon. The delivery of these products can share a truck and therefore increase the delivery frequency. Optimally all of the suppliers should be integrated into the value stream. The plant must work to attain this level of integration with all of the suppliers.

3.3.9 Step 12: Align product development

The Rainbow Production System Design occurred in isolation from the design of the product. The two teams were physically located in different sites and there was little communication between them. The previous chapter describes the importance of the collaboration of these two organizational functions to guarantee the success of the product. In the future, special attention must be paid to the interactions between the development of the product and the development of its manufacturing system. It is important to approach both these development processes with cross-functional teams in order to make informed decisions.

Chapter 4: Case Study: Visteon Electronics Plant

This section includes the work performed by the author together with Guillermo Oropeza and Prof. David S. Cochran at one of Visteon's electronics plants.

The production system analyzed at this plant manufactures Electronic Engine Controllers (EECs). These devices are responsible for engine control functions generally described as power train control. Basic functions controlled by the EECs include spark timing control (what a distributor and timing belt used to do), transmission control, and engine management (air-fuel mix and diagnostics).

The manufacturing process consists of four stages: Two Surface Mount Device (SMD) processes, lamination, and packing. During SMD processing different components populate both sides of a circuit board. At lamination, the populated circuit board is assembled with the connector and the casting case; here also the software is programmed into the board. During packing, automated transfer lines and robotic arms prepare ready-to-ship products.

The Visteon Electronics plant is particularly interesting for the analysis as it performs the lamination of the EECs using two very different approaches. One uses traditional asynchronous high-speed transfer line and the other is a single pece flow "lean" cell.

The scope of this project is to analyze the material and information flow of this product as it is processed through these different systems. Also, by using the Manufacturing System Design Decomposition, a thorough assessment of the two lamination methods is made. The results of this analysis are compared to the evaluation of these two systems using traditional performance metrics. By using the MSDD evaluation method, we are able to point out potential areas for improvement at the implementation level of the cell, which are not immediately obvious from just observing performance results.

Furthermore, by using the Equipment Evaluation Tool [Gomez, Dobbs and Cochran, 2000], which was derived from a subset of the MSDD related to this area, an analysis of some of the stations at the two systems is performed. This shows how equipment designed with a systems perspective leads to improved overall system performance.

4.1 Material and Information Flow

4.1.1 Material Flow

The manufacturing system studied produces 200-300 different types of EECs to accommodate many different vehicle variations. The manufacturing system starts with approximately 20 different circuit board configurations that constitute the different product family groups. These boards are populated with electronic components in different patterns to make up to 60 different types of ready-to-assemble boards (approximately 3 patterns per family group) as shown in Figure 4-1. Because of the similarities between board designs and to reduce the scheduling complexity, the products were grouped into families. Each one of these 60 populated boards represents a product family. At lamination, the boards can be programmed differently to form the vast variation of EECs.

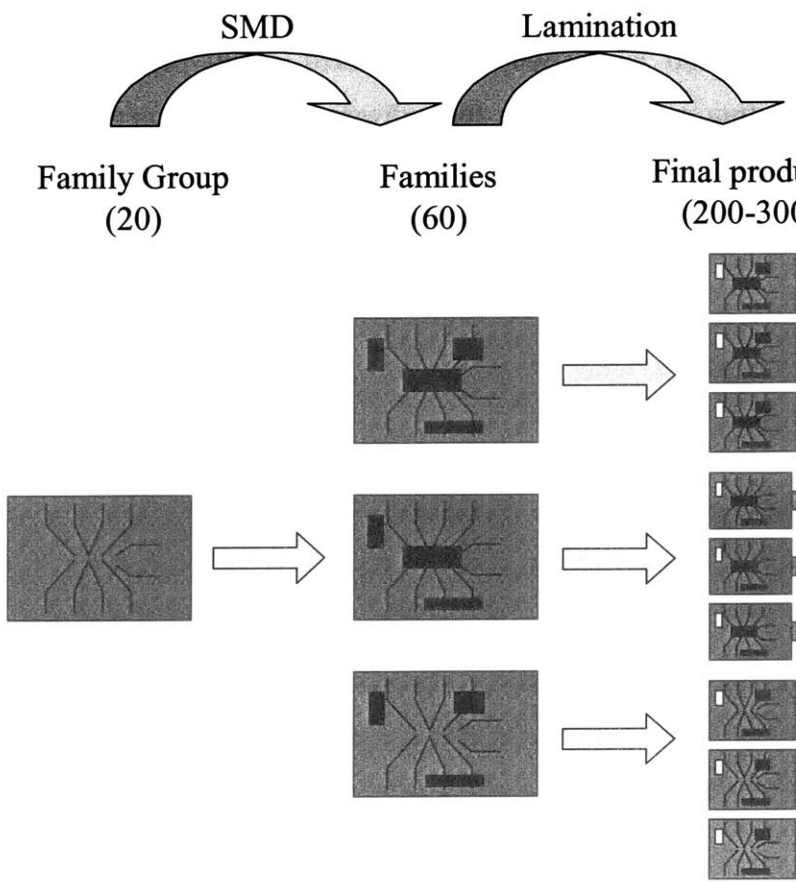


Figure 4-1: EEC production steps

4.1.1.1 SMD Process

During the SMD processing, the electronic components are mounted to a Printed Circuit Board (PCB). The SMD process lines are grouped in identical line pairs dedicated to group families (see Figure 4-1). Each SMD line pair is composed by a line that populates the top-side of the board and another line that populates the bottom side of the board. The SMD lines are configured to run autonomously with the exception of manual loading and unloading of the electronic components. Three operators are in charge of these tasks, as well as performing changeovers, replenishment of material and supervision of the automatic machines. Figure 4-2 shows a schematic representation of one of these lines.

Parts that have been populated on their upper side are directly transferred to the contiguous bottom process line located across the hall. Between the two high-speed lines, there is a small amount of inventory. The Work-In-Process (WIP) between the two lines can be up to a half day of production (472 parts for each line pair, or about 3000 parts for all six line pairs).

The operating pattern for these lines is three shifts of 8 hours. There are two 15-min. breaks and a lunch break of 30 min. per shift. This leaves a total of 21 available working hours in a day.

At the SMD lines, the boards are stacked manually in a loading station at the beginning of the line. The PCBs are automatically transferred one-by-one to the conveyor that transports them through the different processes in the line. The first process is the application of solder paste. The material is applied to the PCBs in a printer-like fashion according to a pattern that matches the electric contact points of each specific board type. The next step is the automatic visual inspection of the solder pattern: measuring whether the right amount of solder paste has been applied at the right location. This operation is done at the automatic visual tester.

After inspection, adhesive is applied to the PCB to prepare it for subsequent chip placement at the next station. The adhesive is needed to hold the main chip in place due to its size and weight. This operation is only performed on the SMD line that processes the top-side of the board and represents the only difference between the top and bottom process. The other electronic components are held in position by the solder paste previously applied. With the solder and adhesive in place and after successful testing, the boards go through the first SMD machine. The function of the SMD machine is to place the different electronic components required for a particular product. These components are supplied in reels, which are mounted on the SMD machines.

Most of the SMD machines used at this plant have reels on both sides of the conveyor and there is a dispenser for each reel location. As the part moves through the machine, each dispenser inserts the components as needed in a process termed "board population."

Once populated, the boards go through the reflow oven, which melts the solder paste to create a solid electrical connection. The average throughput time for this process is approximately 20 minutes.

Finally the boards are automatically unloaded into magazines of 27 parts. These containers wait until an operator transfers them across the hall, to initiate a similar process for the bottom side of the PCB.

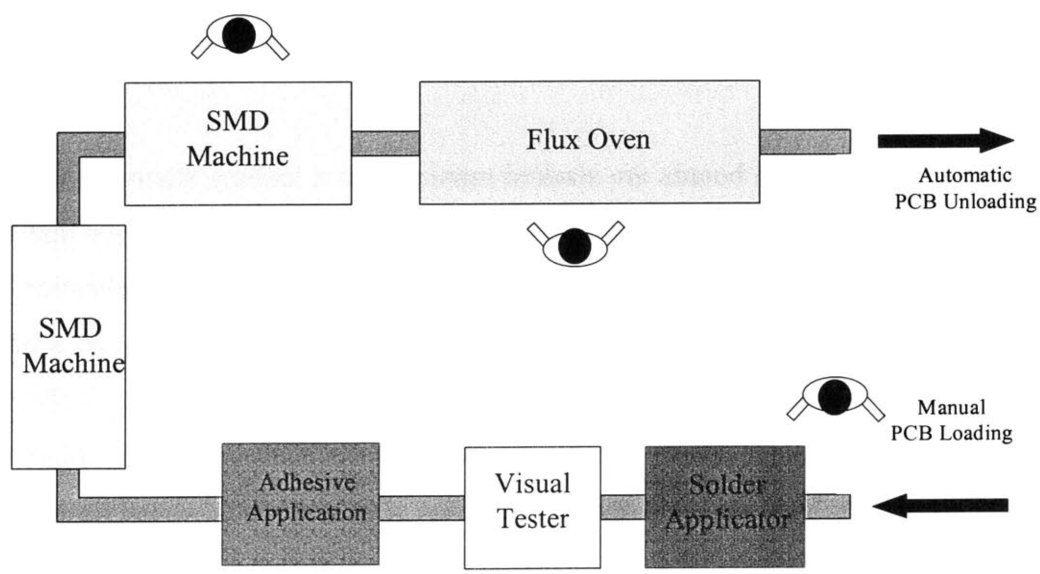


Figure 4-2: SMD Top-Side Process Sequence

4.1.1.2 Lamination Process

The populated boards can be routed through two different lamination processes. The first process includes two high-speed lines with a cycle time of 10 sec and the second consists of a volume flexible "lean" cell with a cycle time of 50 sec. Each high-speed line has an annual capacity of 1.6 million parts, whereas the cell produces only 350,000 parts per year. The relative size of each line is shown in Figure 4-3. At a first glance, there is a marked difference in the two systems, as can be seen in Figure 4-4 and Figure 4-5. The subsequent sections herein will quantify these differences and provide a rationale for a sound system evaluation.

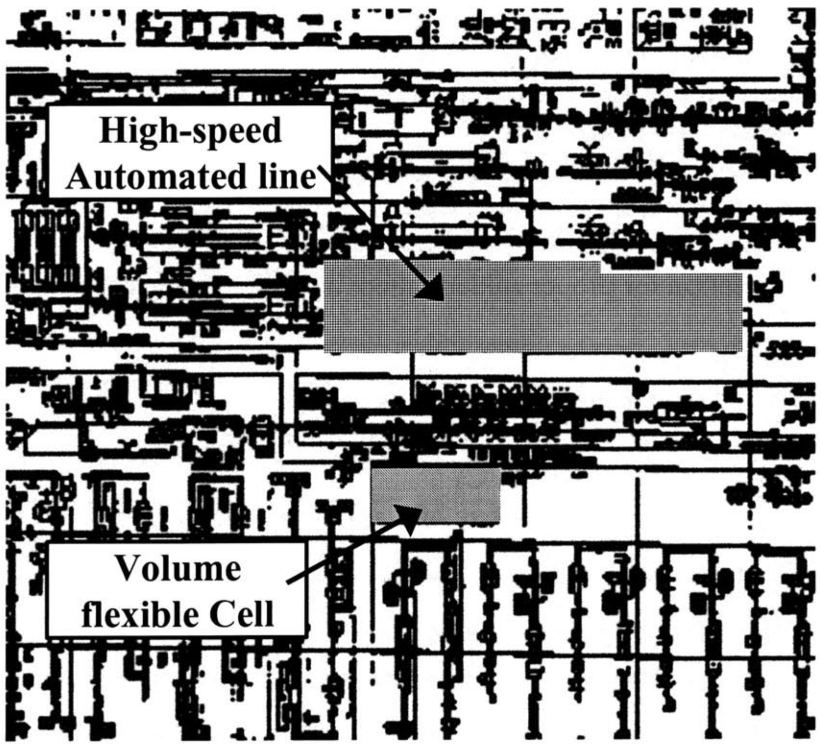


Figure 4-3: Relative Size Comparison between Cell and automated Line

4.1.1.2.1 High-speed, Automated line process sequence

Most of the EECs at the plant are assembled at one of the two high-speed lines. Figure 4-4 shows a diagram of the process sequence.

The sequence of process steps is described in Table 4-1 and illustrated in Appendix D.

Table 4-1: High-speed Line Process Steps

1. Automatic unload of PCBs from the magazines and into the conveyor.
2. In-circuit test of the PCBs. In the future, this step will take place at the SMD process lines. This step is required to ensure that the necessary components are put in place.
3. Mating of the PCB with the prepared casting-connector. Previous to this point, an incoming line branch delivers the assembled casting-connector. The lamination material has also been applied to the connector subassembly in preparation for its mating with the PCB.
4. Screw board to casting. A six-spindle fully automatic screw-driving machine fastens both components.
5. Solder connector to board. A rotating machine picks up the boards and dips the connector in a curtain of molten solder.
6. Bar code reading to identify the PCB family
7. Visual inspection for proper solder pattern as well as to detect housing shape integrity
8. Voltage-stress-test station
9. Conformal coating (dip in silicon and oven curing)
10. Bottom plate placement and attachment with screws
11. Gasket application (to seal EEC)
12. Burn-in process to induce failure of weak components
13. Unload

4.1.1.2.2 Volume flexible cell process sequence

The "lean" cell represents an innovative process alternative at this plant for the lamination of the PCBs. The EECs produced by this cell are mainly supplied to a single vehicle assembly plant. Although the product is the same as that produced by the high-speed lines, the process in the cell illustrated in Figure 4-5 and Appendix E, and described in Table 4-2 varies slightly from the high-speed line sequence described above. The variations in the process were introduced to satisfy special customer requests. The flexibility of the cellular approach allowed these modifications.

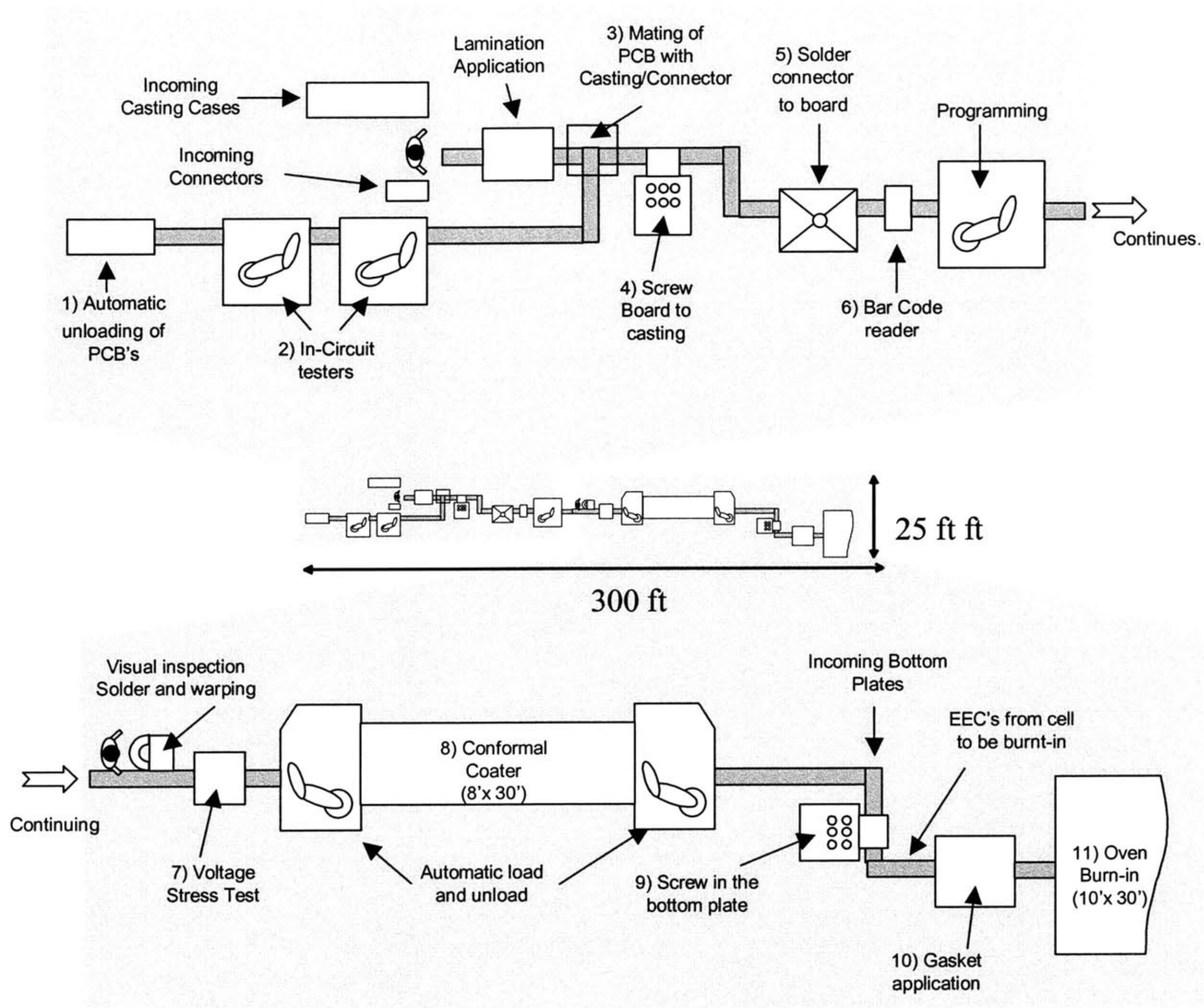


Figure 4-4: High-speed, asynchronous, automated assembly line layout (CT=10sec.)

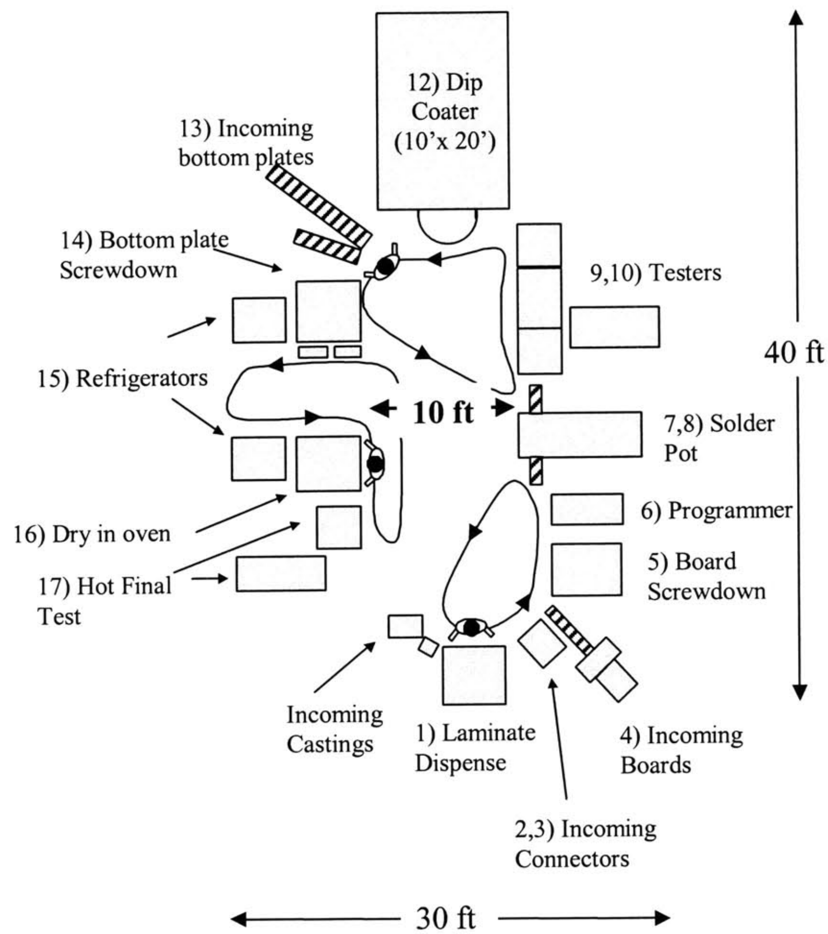


Figure 4-5: Lamination "Lean" Cell Layout

Table 4-2: Lamination Cell Process Steps

1. Laminate castings. A similar process to the high-speed line is used. The larger cycle time of the cell allows slower operation and reduced machine complexity.
2. Visual inspection for good adhesive beads
3. Assemble connector to casting (Casting/Connector Assembly Station)
4. Place PCB onto casting subassembly
5. Screw-down of PCB into casting subassembly. The larger cycle time of the cell allows a two-spindle machine to be used as opposed to the six-spindle machine at the high-speed line.
6. Program input
7. Solder connector to board
8. Visual inspection of solder
9. Native-mode test
10 Reset test
11. Ambient test
12. Dip coat and curing (conformal coating)
13. Placement of bottom & top cover plates into subassembly
14. Screw-down cover plates. Same machine as step 5
15. Cold chamber process (batches of 20 parts)
16. Dry in oven
17. Hot final test

Notice that the sequence in Table 4-2 does not include the burn-in process. After the hot final test, the EECs are transferred to the automated high-speed lines to be processed at the burn-in oven. The units are incorporated into the line just before the gasket application station, at the discretion of the line workers. From this point on, the units follow the same path as those processed in the high-speed lines.

The cell requires three operators but can be operated with one, two or more operators as volume changes. The standard work routines for the three-operator configuration can be seen in Figure 4-5 and are shown in greater detail in Appendix F. It is worth noting that these work instructions are incomplete, as they do not provide information related to the required completion time for each task. The operating pattern for these lines is two 8.5-hour shifts and one 7-hour shift, with minimal overlap.

Some of the benefits of the cellular approach can already be appreciated from Figure 4-5. The fact that operators perform their tasks while walking as opposed to sitting is better from an ergonomics point of view. By working in small teams, people tend to develop a sense of ownership for the parts they build which results in an improved morale in their environment. Also, as the following sections will show, the equipment is more easily accessible which promotes cross learning and enables better balancing to accommodate fluctuating volume requirements.

4.1.1.3 Packing

Once the EECs are fully assembled, the units are automatically unloaded from the lamination high-speed line. Then the EECs proceed through a system of accumulating conveyors (serving as an automated buffer) into final packing, where a robotic arm prepares the boxes for shipment. Each box is filled with 18 EEC units.

Some boxes are sent directly to the staging area to be shipped and others are held in inventory for some days at the Automatic Storage / Retrieval System (AS/RS). WIP in the pack area is about 600 units in the automated line and 750 modules in the AS/RS.

4.1.2 Information Flow

4.1.2.1 Scheduling

The scheduling and planning of production is supported by the software package Rhythm™ [i2 Technologies]. This software takes existing orders and assists in creating a production plan that smoothes the weekly production so that the same volume is produced every day. It also serves as an aid to level the production plan, that is, reducing the number of consecutive parts of the same type scheduled for production. The plant is able to rely on a month of orders from the customer to create a demand forecast and plan its production. These orders are seldom changed, but the schedule is revised each week to account for any modifications that the customer may make. The software assumes an infinite capacity plant and it is the scheduler's responsibility to level production with the aid of the software.

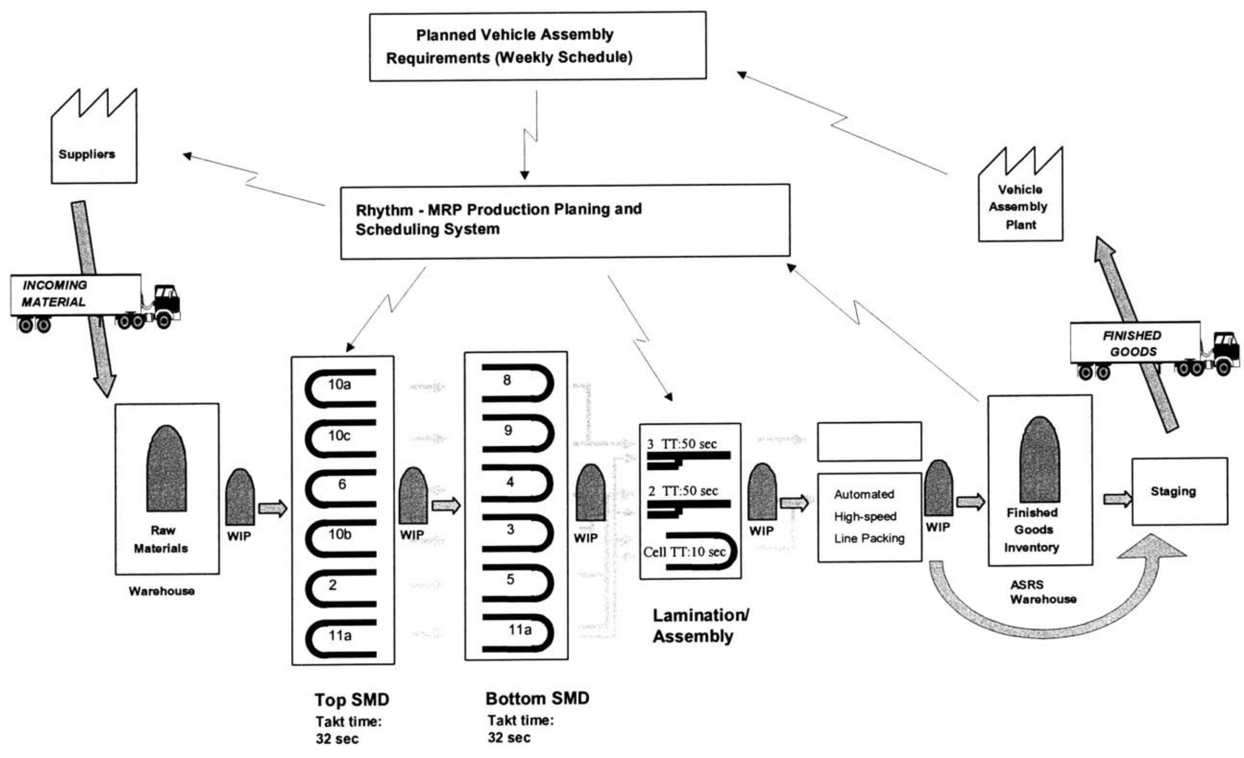


Figure 4-6: Value Stream Map of the EEC Production

The production is scheduled at two points: SMD first pass (top) and lamination as shown in Figure 4-6. The system is scheduled at SMD because it is perceived as the most constrained operation. The change-over setup times have a significant impact on the capacity of the lines. For scheduling purposes, the throughput time from SMD to final packing is assumed to be two days.

Information on volume and mix is sent to the first SMD line. At this point, the information about the mix is only specific to product families; final product variations are not yet determined. Products flow in a FIFO manner through the rest of the downstream operations. When the EECs reach lamination, the bar code is read to determine the product family type. With this information, the specific software is programmed into the EEC according to the production schedule determined by Rhythm™.

Purchase orders for the supplied materials are produced using an MRP system. The interaction between the production processes, suppliers and scheduling center is represented in the value stream mapping in Figure 4-6.

4.2 Lamination Analysis

4.2.1 Observed Performance at Lamination: High-speed Line and Cell

In order to better appreciate the difference in performance between the lamination systems, several categories were quantified and summarized in Table 4-3. These values, normalized by production volume, were obtained from the observed performance of the two systems. It is interesting to note that even though the cell requires more direct labor, it outperforms the automated line in all the other metrics considered. Most importantly, the cell is more effective in producing good parts per labor hour than the high-speed, automated line.

Given that traditional accounting systems in mass production plants strive to reduce direct labor, most of the other benefits that cellular manufacturing promotes are often overlooked. Table 4-3 attempts to illustrate this point.

Table 4-3 Observed performance at the lamination high-speed line and cell (Normalized for volume)

Metric	Cell	High-Speed
Floor Area (sq. ft.)	1	1.37
WIP within lamination	1	1.02
Throughput time (hrs)	1	2.33
Capital Investment (M)	1	1.57
Direct Workers	1	0.44
Indirect Workers	1	2.19
Defects (assignable to lam. sequence)	1	2.50
Good Parts/labor-hour (includes direct and indirect labor)	1	0.76*
Capacity	1	1.00

* A smaller number indicates poorer performance.

Even when this evaluation method suggests that the preferred production approach is the cellular one, there is not enough information that can be derived from these numbers to improve the performance of the system. The next section takes a different approach to analyze the performance of the two systems. By using the Manufacturing System Design Decomposition [Cochran and Reynal, 1997], potential improvement areas at the implementation level are identified.

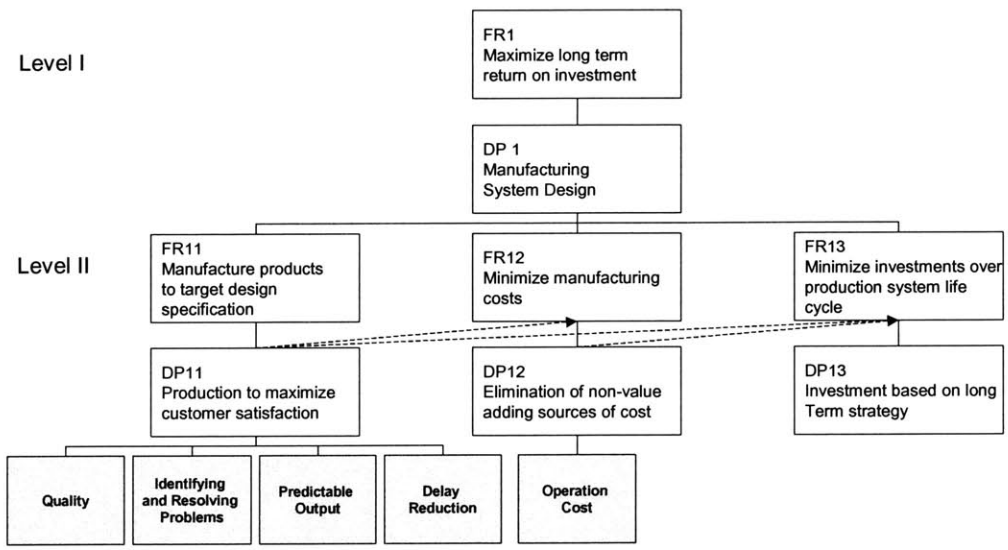
4.2.2 Analysis of Lamination Processes using the MSDD

4.2.2.1 The Manufacturing System Design Decomposition (MSDD)

The MSDD is a tool to aid the designer of manufacturing systems in identifying key concepts to incorporate into the design of a system. The methodology used is a decomposition based on axiomatic design [Suh, 1990] in which the Functional Requirements (FRs) of the system are mapped to a physical implementation or Design Parameters (DPs). The process begins by identifying the highest-level goal of a manufacturing system, maximizing return on investment, and decomposing it systematically into lower-level requirements (Figure 4-7).

For every FR there is a corresponding DP, which dictates what needs to be done to achieve the corresponding requirements [Cochran, 1999]).

The lowest level FRs and DPs gather the concepts of lean manufacturing previously considered but rarely implemented using a comprehensive approach. The MSDD not only dictates what needs to be implemented in the shop floor in both a static and dynamic setting, but it provides a means to communicate goals for performance measurement across different levels of the organization. Therefore, the MSDD is useful in designing, evaluating and controlling manufacturing systems. [Cochran, Arinez, Duda, Linck, 2000]



$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \end{Bmatrix}$$

Level II relationship matrix

Figure 4-7: Upper level FRs and DPs of the MSDD

Furthermore, the MSDD can be used to identify potential areas for improvement [Cochran, Neise, 2001]. The justification for the use of the MSDD as a design tool can be reinforced by tracing the degree of conformance of each system design relative to the MSDD. The conformance to the MSDD can be compared to the performance of each system as defined by traditional metrics described in the previous section. The results based on the MSDD comparison, which indicate system design adequacy, are consistent with the results using traditional performance measurements.

4.2.2.2 Evaluation of the High-Speed Lamination line using the MSDD

This section shows the degree of conformance of the high-speed lamination line used at this plant to the MSDD. The process of evaluation is to consider only the leaf FRs as shown in Figure 4-8. The reason for evaluating only these FRs is that it is sufficient to show that one leaf FR is not satisfied to show that the parent FR is not fulfilled. Also, since these FRs are at the lowest level in the MSDD, they can be easily evaluated because an implementable DP can be assigned to them.

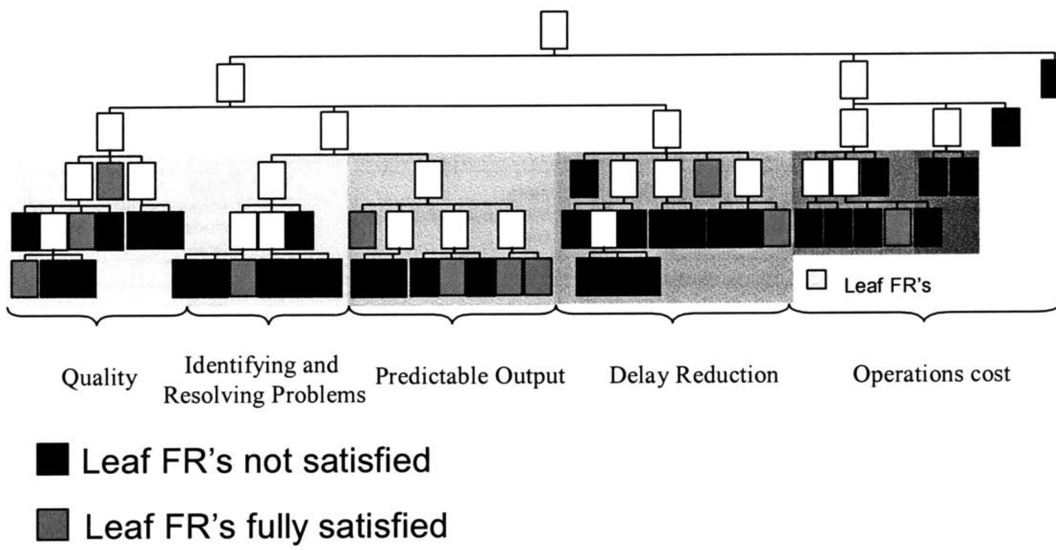


Figure 4-8: High-Speed Line Evaluation Using the MSDD

A grade of 1 was used to represent an FR that is fully satisfied and a grade of 0 for an FR that is weakly or not satisfied at all; the grades are shown schematically below in Figure 4-8. Appendix G shows in more detail the grades given for each of the leaf FRs for both the lamination high-speed line and the cell. The conformance to the MSDD FRs by areas is summarized in Table 4-4.

4.2.2.3 Evaluation of "Lean" Cell Lamination system using the MSDD

The methodology used to assess this system is the same as that used to evaluate the high-speed automated line. The satisfaction of the leaf FRs of the MSDD is shown schematically below in Figure 4-9.

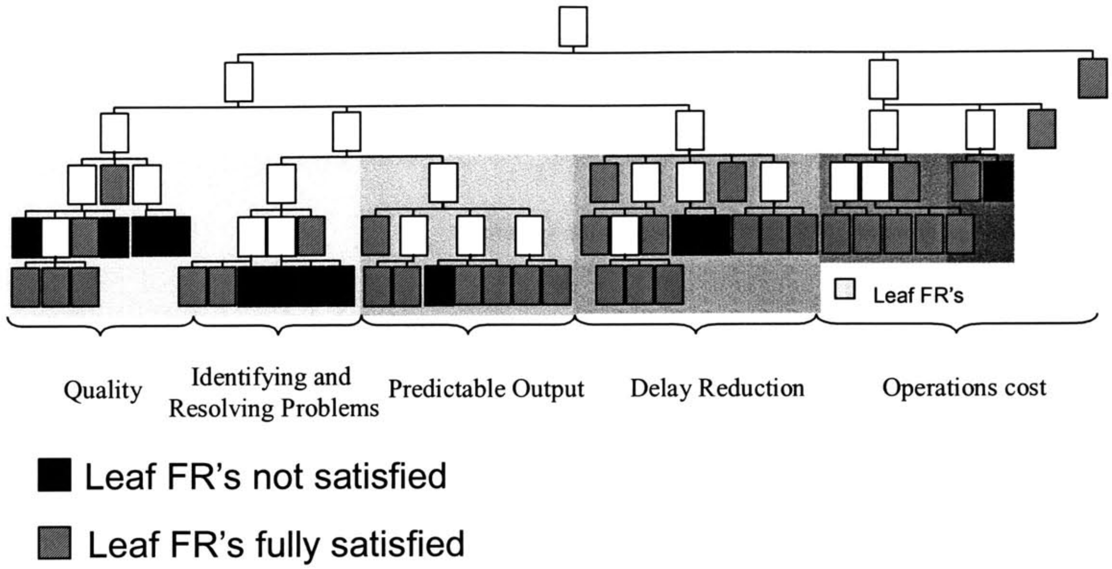


Figure 4-9: Lean Cell Evaluation Using the MSDD

The conformance to the MSDD functional requirements for the cell is also summarized in Table 4-4. By using this analysis, we can observe where the system can be improved. Due to the nature of the MSDD, the leaf FRs can be traced to implementable solutions. Therefore, special attention can be paid to low performing FRs. The next section outlines the low performing leaves based on this approach for present and future cellular implementation improvements.

Table 4-4: Satisfaction of MSDD leaf FRs at Lamination

FRs Injection Molding	High-Speed	Cell
Quality	3 of 9	5 of 9
Identifying and resolving problems	1 of 7	3 of 7
Predictable output	4 of 8	8 of 8
Delay reduction	2 of 12	10 of 12
Operations cost	1 of 10	9 of 10
Total	**11 of 46**	**35 of 46**

4.2.3 Recommendations for cellular implementation derived from the MSDD

Based on the experience of this first cellular implementation in the lamination area, and using the MSDD-based analysis from the previous section, some recommendations can be made for present and future cellular implementations as well as for overall plant design.

It is first worthwhile to note that, in comparison with the high-speed line represented by Figure 4-8, the schematic in Figure 4-9 reveals a design that more adequately satisfies the overall system goals. This result is an indication that the design of the cell achieves more of the FRs congruent with a world-class production system.

Table 4-5: Low performing FR/DPs for the cellular system

FR/DP	FR	4.2.3.1.1.1.1.1.1 DP
Q11	Eliminate machine assignable causes	Failure mode and effects analysis
Q14	Eliminate material assignable causes	Supplier quality program
Q31	Reduce noise in process inputs	Conversion of common causes into assignable causes
Q32	Reduce impact of input noise on process output	Robust process design
R113	Identify what the disruption is	Context sensitive feedback
R121	Identify correct support resources	Specified support resources for each failure mode
R122	Minimize delay in contacting correct support resources	Rapid support contact procedure
R123	Minimize time for support resource to understand disruption	System that conveys what the disruption is
P131	Reduce variability of task completion time	Variance in task completion time
T31	Provide knowledge of demanded product mix (part types and quantities)	Information flow from downstream customer
T32	Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment
I2	Eliminate information disruptions	Seamless information flow (visual factory)

However, based on the MSDD analysis, some leaf FRs were not satisfied by the current cellular design. Identifying these FRs gives valuable information for improving the performance of current and future systems. Due to the nature of the leaf FRs, a corresponding DP can be implemented and tracked to them. The FR/DP pairs that received a grade of 1, and therefore the ones that provide room for improvement and attention, are outlined in Table 4-5.

In order to address some of these low performing FRs, it is necessary to zoom out to analyze the plant again with a broader perspective. As can be seen in Table 4-5, some problems with traceability of defective incoming parts, information disruptions, and repair procedures still remain. Furthermore, the standardized procedures to respond to these types of disruptions must be designed and communicated to the workforce. Another area where the design must be improved is the standardized work definition. It should include information on the expected time to complete each task. Also, the system should be able to communicate if the pace is being kept or if the system is falling behind.

Although the lamination cell was able to improve dramatically on its predecessors as Figure 4-8 and Figure 4-9 show, the current plant value stream mapping reveals potential areas for improving from a systems perspective on these low performing FRs.

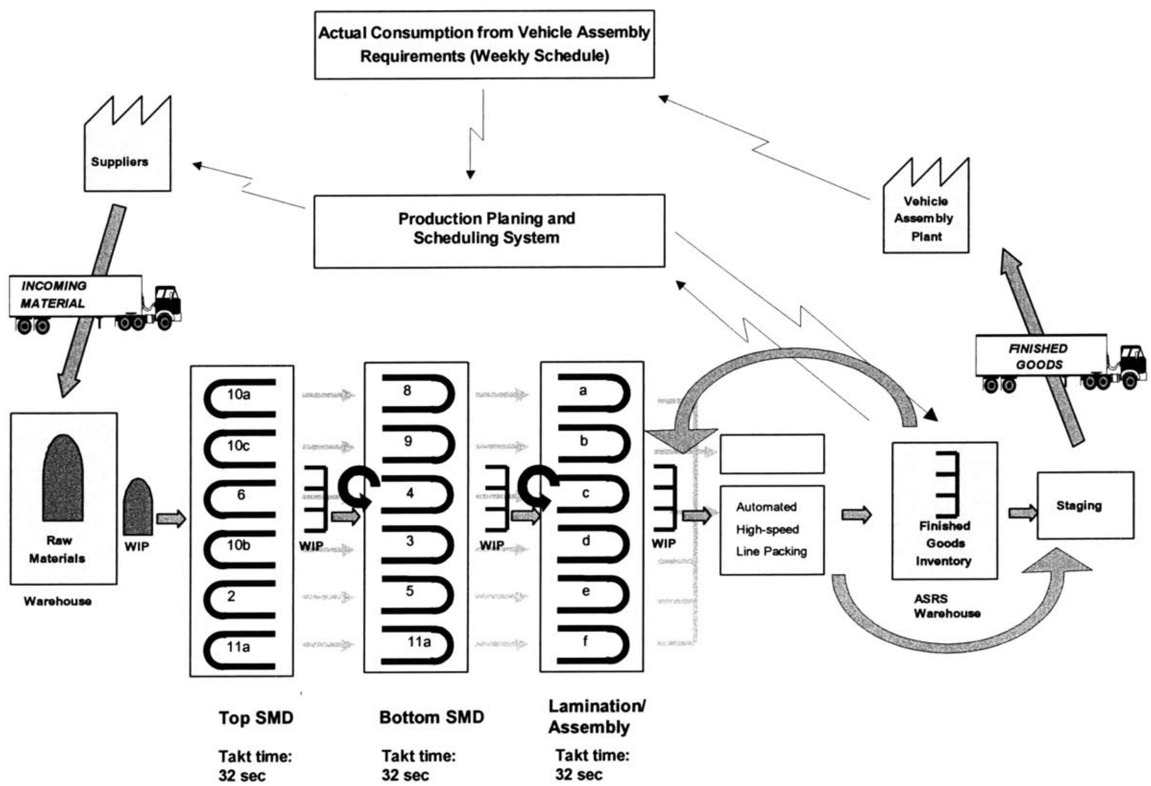


Figure 4-10: Proposed Value Stream Map

Figure 4-10 shows a modified version of the current value stream map at the plant. The fundamental difference is the alignment of lamination with SMD. With this proposed mapping, a lamination line can be dedicated to each SMD pair. This value stream can be in turn dedicated to a particular product or customer. Assigning a value stream to a customer eases defect traceability and correction. Also, the new system presents greater flexibility to accommodate changes in product design or in customer requirements. Furthermore, by laying out the plant in such a way, scheduling can be simplified. As Figure 4-10 shows, only one scheduling point is required at the finished goods supermarket, thereby enabling a pull production system, which allows inventory and cost reduction.

4.3 Equipment Design

4.3.1 Equipment comparison based on the MSDD

One of the most striking differences between the high-speed line and the cell is the equipment used in both assembly systems. One can attribute such differences to the concepts derived from the Toyota Production System [Monden, 1993, Ohno, 1988, Shingo, 1989] and how these concepts define the way the equipment should be designed. However, practices that have given good results in some companies do not necessarily yield the same results in all companies. Generalizing specific machine design guidelines from company to company naturally restricts the potential to go beyond competitors. The MSDD serves as the basis to understand why the equipment should be designed in a "lean" way, and to allow one to improve on other world-class equipment designs.

As described previously, the MSDD allows us to trace high-level objectives of a manufacturing system into lower-level physical implementations at the shop floor. The FR-DP pairs that in some way affect equipment design and operation have been identified [Arinez and Cochran, 1999] to understand the cause-effect relationship between goals and implementable steps.

To evaluate how well the FR-DP pairs related to equipment design are satisfied, the Equipment Evaluation Tool (EET) is used [Gomez, Dobbs and Cochran, 2000]. The EET is used to assess how well a particular piece or set of equipment conforms to the requirements imposed by the equipment-related FRs. This evaluation procedure can be used to ensure that equipment designs are better aligned with overall manufacturing system objectives. The tool can also be used to identify problems in existing equipment and to set goals for the improvement of equipment to better satisfy the requirements placed on it by the MSDD [Gomez, Dobbs and Cochran, 2000].

4.3.1.1 Application of the Equipment Evaluation Tool

The Equipment Evaluation Tool is used to analyze the differences in equipment design at the high-speed line and the cell. Three similar processes were selected from both lamination systems and measured with the EET. The processes analyzed are: PCB-Casting screw-down, solder application, and conformal coater loading. Figure 4-11 to Figure 4-13 show the processes being evaluated and Table 4-6 summarizes the results of the evaluation.

Table 4-6: Evaluation scores of processes at both lines using the EET.

Process	"Lean" Cell	High-speed line
PCB-Casting screw-down	**4.9**	**2.5**
Solder application	**4.7**	**3.6**
Conformal coater loading	**5.1**	**3.1**

The casting screw-down process is shown in Figure 4-11. The longer cycle time of the cell allows for simpler equipment. A 2-spindle screw-gun is able to perform the operation performed by the 6-spindle surrogate in the high-speed line (i.e. 10 sec. cycle time) more effectively. With lower complexity, the 2-spindle machine is more reliable and easier to maintain. The design is more flexible and can better accommodate changes in the design of the product. The evaluation shown above reflects these advantages.

The next process evaluated, the solder application, is illustrated in Figure 4-12. The equipment used is, again, simpler and more accessible. The simplicity of this equipment results from designing it to operate at the longer cycle time of 50 seconds.

When loading the conformal coater, two greatly different processes are used. As Figure 4-13 shows, the cellular approach fully utilizes labor capabilities. Using an operator to perform this task enables simultaneous visual inspection, which helps to anticipate production disruptions. Also, the same operator is used to unload the coated boards. On the other hand, automating this task requires a multi degree-of-freedom robotic arm. An additional station for automatic inspection is required. Also, a second robot for unloading the boards is needed. The robot itself is a complex piece of machinery requiring constant maintenance. But it represents a safety hazard for humans. Therefore, the robot should be confined from human contact making access for repairs more intricate.

From these results, we can observe that complexity results from speed and full automation of material handling. Although simpler, the equipment at the cell is consistently better designed to achieve the system-wide goals. Higher marks are earned for the equipment used at the cell, implying that this equipment satisfies the FRs related to equipment design, which in turn enables the manufacturing system to achieve higher-level objectives.

Cellular Equipment – Cycle Time : 50 sec **High-speed Line Equipment – Cycle Time: 10 sec**

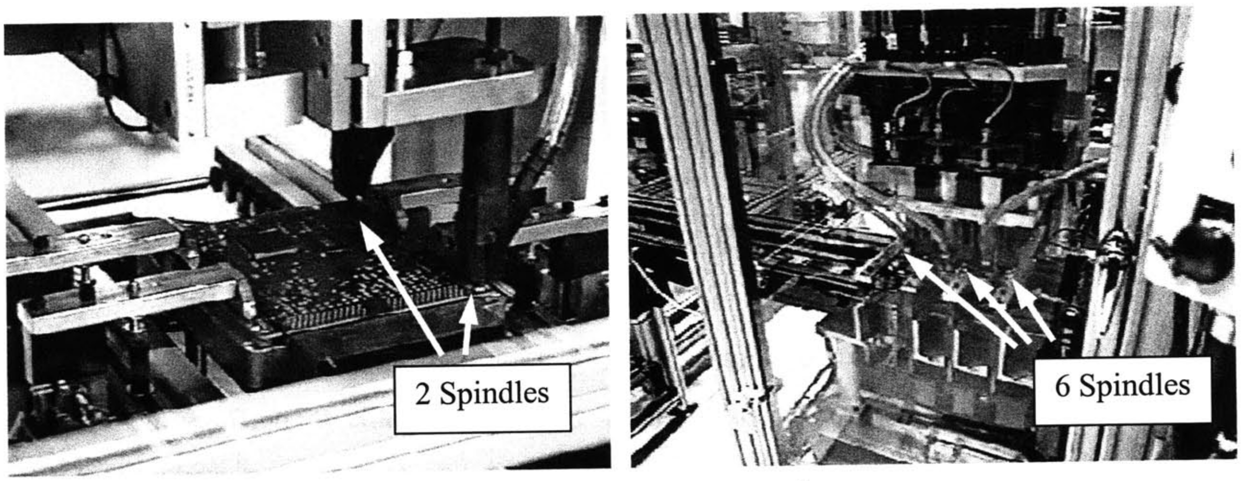


Figure 4-11: PCB-Casting screw-down

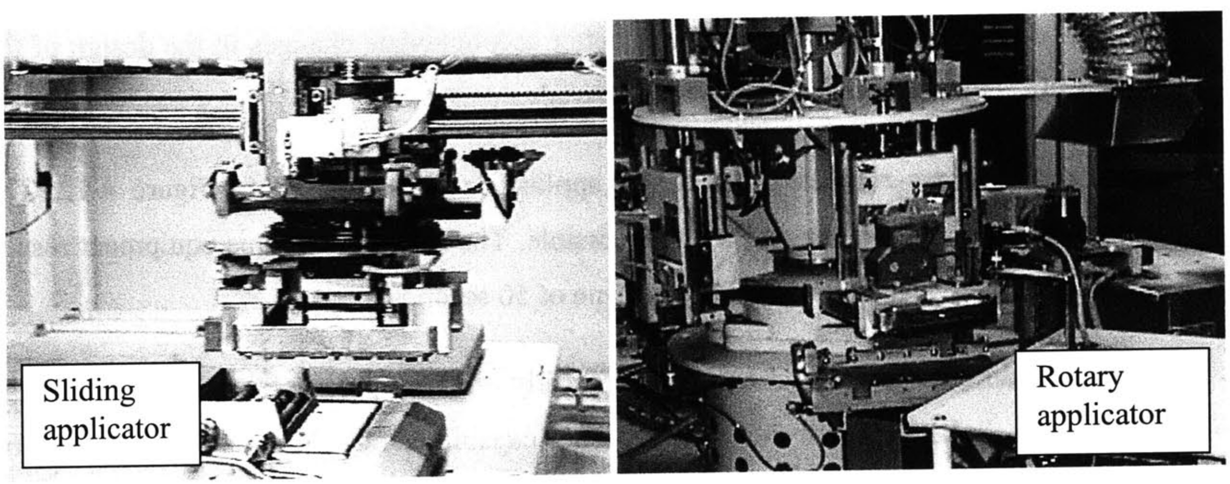


Figure 4-12: Solder application at the cell

Cellular Equipment – Cycle Time : 50 sec

High-speed Line Equipment – Cycle Time: 10 sec

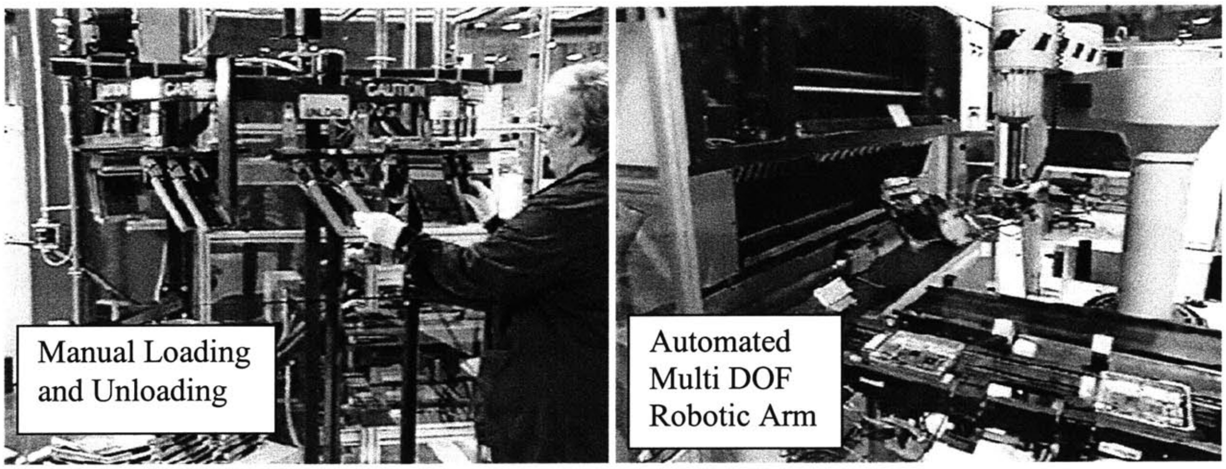


Figure 4-13: Loading conformal coater

Conclusion

This thesis recognizes the complexity in Production Systems Design and the difficulty of identifying a logical path to follow when thinking about the features of a system. To approach this problem, it presents the Production System Design (PSD) Framework (based on the Manufacturing System Design Decomposition developed at MIT) as a methodology for producing designs that are able to achieve the enterprise objectives. In particular, the work concentrates on the Production System Design and Deployment Steps from the PSD Framework as a roadmap to approach the intricate process of designing the Production System and its subsequent implementation.

The PSD Framework was applied to the design of the Production System for an automotive rear differential. The fact that this system will only produce one product type simplified the design process. The design was done following each one of the Production System Design and Deployment Steps. Throughout the design process, a few obstacles were encountered like the presence of business policies that constrain the design space and the difficulty of finding equipment designed with a system perspective. These circumstances make this design unique; it was specially designed to overcome these particular constraints and achieve the system objectives.

Finally, the last chapter includes the work performed at an automotive electronics manufacturing plant. This study achieved three objectives. First, the Electronic Engine Controller (EEC) production process was explained by following the material and information flow. Second, derived from the two different lamination processes, an analysis of the process using a traditional transfer line was contrasted to that of a cellular approach. The observed performance of the two systems was compared to an evaluation based on the Manufacturing System Design Decomposition. Although the two approaches yielded similar overall system assessments, the latter identified areas of potential improvement for the current and future cellular implementations. Finally, by using the Equipment Evaluation Tool, the equipment used in both systems was evaluated. The higher marks attained by equipment designed for cells implies that equipment designed with a systems perspective leads to improved overall system performance.

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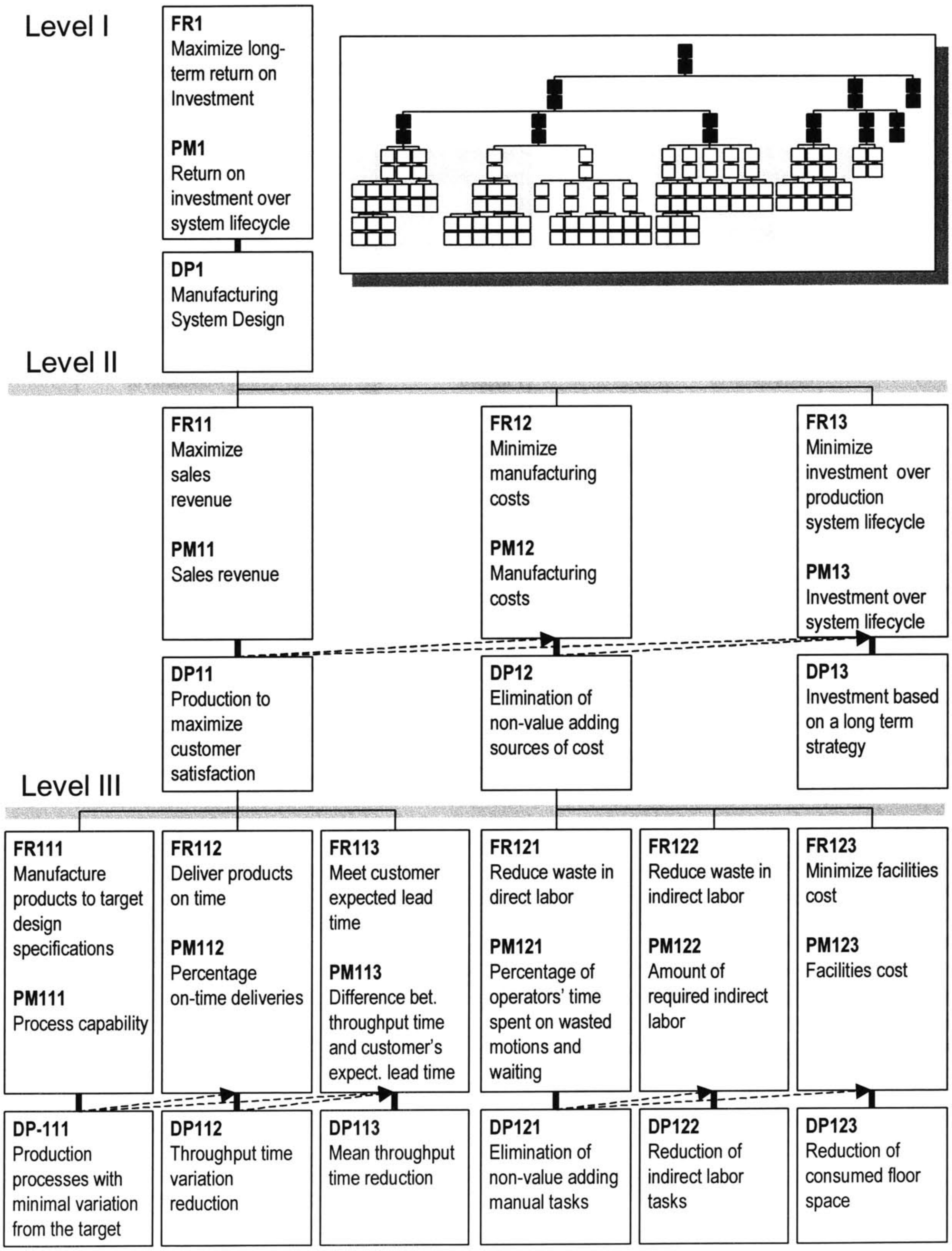
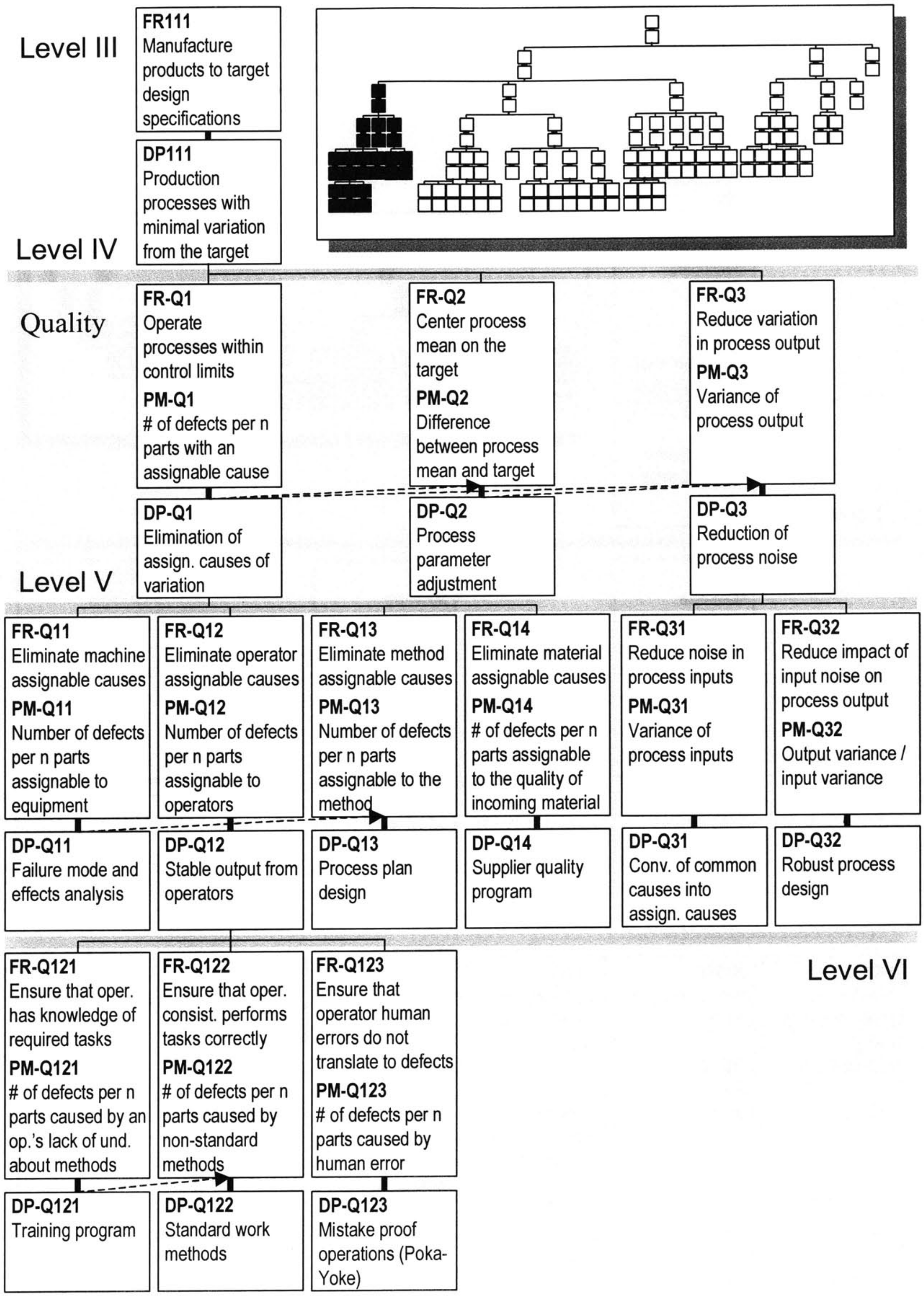
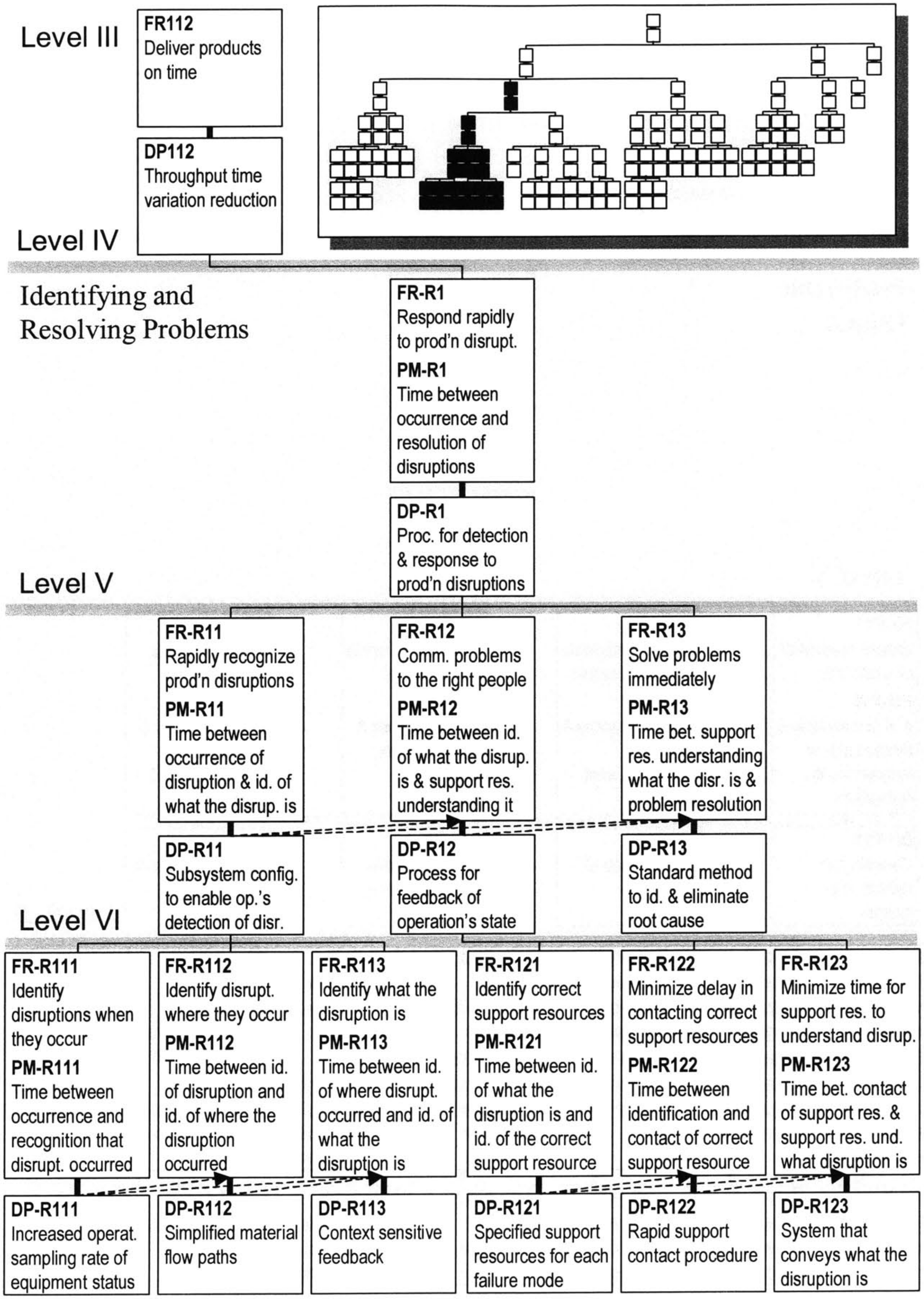
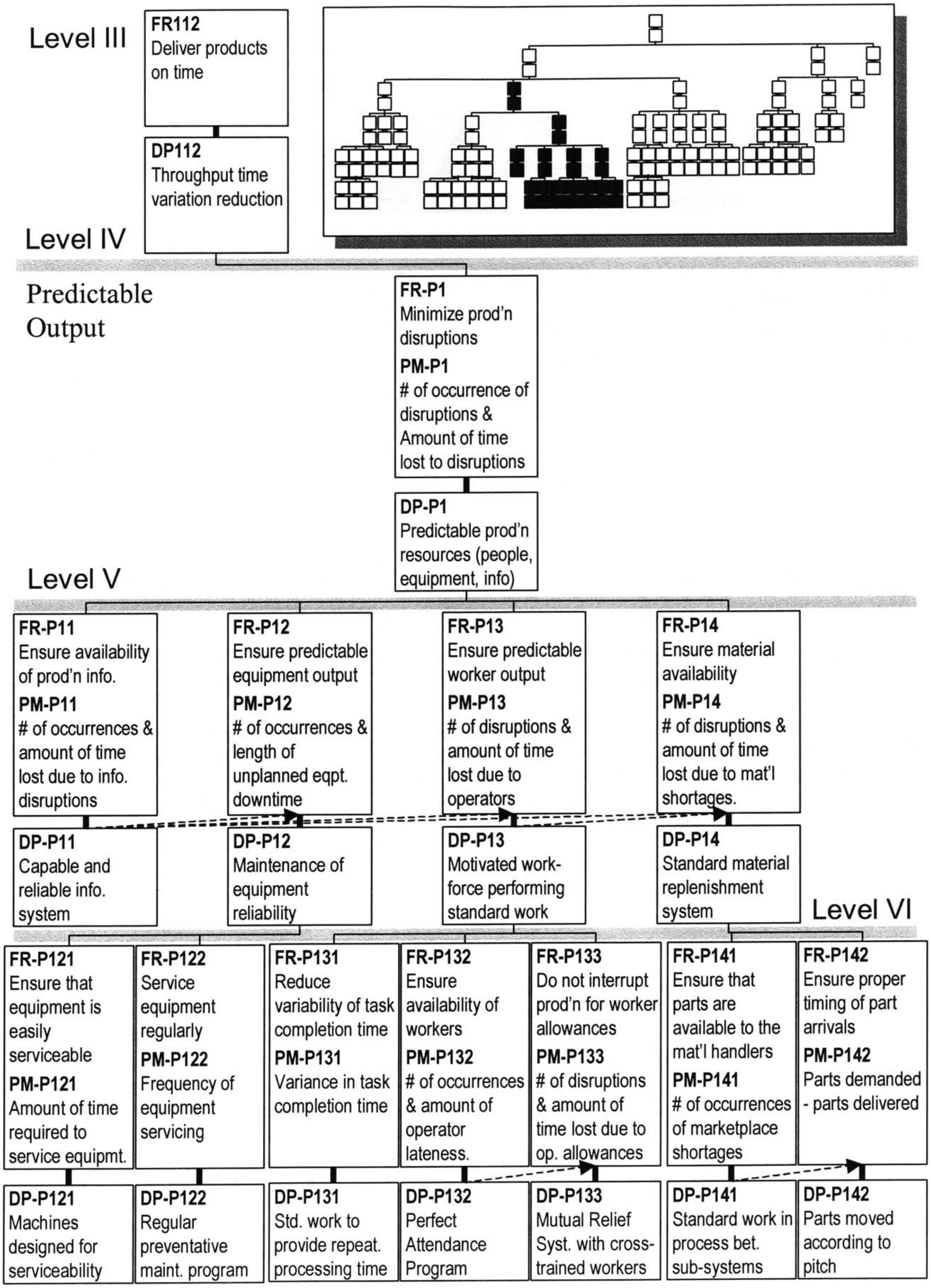
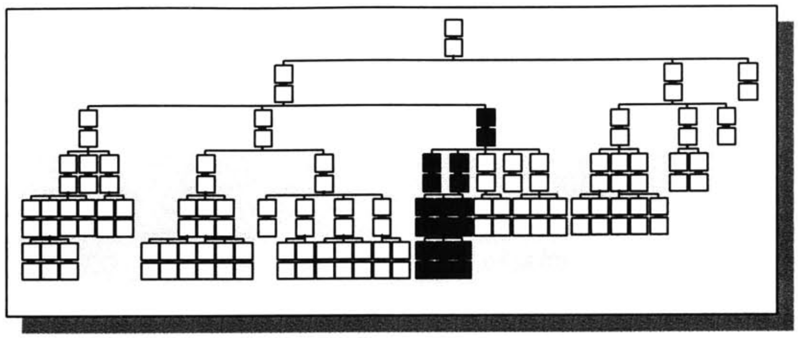
APPENDIX A: Manufacturing System Design Decomposition v5.1




Level III
FR111
Manufacture products to target design specifications
DP111
Production processes with minimal variation from the target
Level IV
Quality
FR-Q1
Operate processes within control limits
PM-Q1
# of defects per n parts with an assignable cause
FR-Q2
Center process mean on the target
PM-Q2
Difference between process mean and target
FR-Q3
Reduce variation in process output
PM-Q3
Variance of process output
DP-Q1
Elimination of assign. causes of variation
DP-Q2
Process parameter adjustment
DP-Q3
Reduction of process noise
Level V
FR-Q11
Eliminate machine assignable causes
PM-Q11
Number of defects per n parts assignable to equipment
FR-Q12
Eliminate operator assignable causes
PM-Q12
Number of defects per n parts assignable to operators
FR-Q13
Eliminate method assignable causes
PM-Q13
Number of defects per n parts assignable to the method
FR-Q14
Eliminate material assignable causes
PM-Q14
# of defects per n parts assignable to the quality of incoming material
FR-Q31
Reduce noise in process inputs
PM-Q31
Variance of process inputs
FR-Q32
Reduce impact of input noise on process output
PM-Q32
Output variance / input variance
DP-Q11
Failure mode and effects analysis
DP-Q12
Stable output from operators
DP-Q13
Process plan design
DP-Q14
Supplier quality program
DP-Q31
Conv. of common causes into assign. causes
DP-Q32
Robust process design
Level VI
FR-Q121
Ensure that oper. has knowledge of required tasks
PM-Q121
# of defects per n parts caused by an op.'s lack of und. about methods
FR-Q122
Ensure that oper. consist. performs tasks correctly
PM-Q122
# of defects per n parts caused by non-standard methods
FR-Q123
Ensure that operator human errors do not translate to defects
PM-Q123
# of defects per n parts caused by human error
DP-Q121
Training program
DP-Q122
Standard work methods
DP-Q123
Mistake proof operations (Poka-Yoke)


Level III
FR112
Deliver products on time
DP112
Throughput time variation reduction
Level IV
Identifying and Resolving Problems
FR-R1
Respond rapidly to prod'n disrupt.
PM-R1
Time between occurrence and resolution of disruptions
DP-R1
Proc. for detection & response to prod'n disruptions
Level V
FR-R11
Rapidly recognize prod'n disruptions
PM-R11
Time between occurrence of disruption & id. of what the disrup. is
FR-R12
Comm. problems to the right people
PM-R12
Time between id. of what the disrup. is & support res. understanding it
FR-R13
Solve problems immediately
PM-R13
Time bet. support res. understanding what the disr. is & problem resolution
DP-R11
Subsystem config. to enable op.'s detection of disr.
DP-R12
Process for feedback of operation's state
DP-R13
Standard method to id. & eliminate root cause
Level VI
FR-R111
Identify disruptions when they occur
PM-R111
Time between occurrence and recognition that disrupt. occurred
FR-R112
Identify disrupt. where they occur
PM-R112
Time between id. of disruption and id. of where the disruption occurred
FR-R113
Identify what the disruption is
PM-R113
Time between id. of where disrupt. occurred and id. of what the disruption is
FR-R121
Identify correct support resources
PM-R121
Time between id. of what the disruption is and id. of the correct support resource
FR-R122
Minimize delay in contacting correct support resources
PM-R122
Time between identification and contact of correct support resource
FR-R123
Minimize time for support res. to understand disrup.
PM-R123
Time bet. contact of support res. & support res. und. what disruption is
DP-R111
Increased operat. sampling rate of equipment status
DP-R112
Simplified material flow paths
DP-R113
Context sensitive feedback
DP-R121
Specified support resources for each failure mode
DP-R122
Rapid support contact procedure
DP-R123
System that conveys what the disruption is


Level III
FR112
Deliver products on time
DP112
Throughput time variation reduction
Level IV
Predictable Output
FR-P1
Minimize prod'n disruptions
PM-P1
# of occurrence of disruptions & Amount of time lost to disruptions
DP-P1
Predictable prod'n resources (people, equipment, info)
Level V
FR-P11
Ensure availability of prod'n info.
PM-P11
# of occurrences & amount of time lost due to info. disruptions
FR-P12
Ensure predictable equipment output
PM-P12
# of occurrences & length of unplanned eqpt. downtime
FR-P13
Ensure predictable worker output
PM-P13
# of disruptions & amount of time lost due to operators
FR-P14
Ensure material availability
PM-P14
# of disruptions & amount of time lost due to mat'l shortages.
DP-P11
Capable and reliable info. system
DP-P12
Maintenance of equipment reliability
DP-P13
Motivated work-force performing standard work
DP-P14
Standard material replenishment system
Level VI
FR-P121
Ensure that equipment is easily serviceable
PM-P121
Amount of time required to service equipmt.
FR-P122
Service equipment regularly
PM-P122
Frequency of equipment servicing
FR-P131
Reduce variability of task completion time
PM-P131
Variance in task completion time
FR-P132
Ensure availability of workers
PM-P132
# of occurrences & amount of operator lateness.
FR-P133
Do not interrupt prod'n for worker allowances
PM-P133
# of disruptions & amount of time lost due to op. allowances
FR-P141
Ensure that parts are available to the mat'l handlers
PM-P141
# of occurrences of marketplace shortages
FR-P142
Ensure proper timing of part arrivals
PM-P142
Parts demanded - parts delivered
DP-P121
Machines designed for serviceability
DP-P122
Regular preventative maint. program
DP-P131
Std. work to provide repeat. processing time
DP-P132
Perfect Attendance Program
DP-P133
Mutual Relief Syst. with cross-trained workers
DP-P141
Standard work in process bet. sub-systems
DP-P142
Parts moved according to pitch



Level III

FR113
Meet customer expected lead time

DP113
Mean throughput time reduction

Level IV

Delay Reduction

FR-T1
Reduce lot delay
PM-T1
Inventory due to lot size delay

FR-T2
Reduce process delay (caused by $r_a > r_s$)
PM-T2
Inventory due to process delay

DP- T1
Reduction of transfer batch size (single-piece flow)

DP-T2
Production designed for the takt time

Level V

FR-T21
Define takt time(s)
PM-T21
Has takt time been defined? (Yes / No)

FR-T22
Ensure that prod'n cycle time equals takt time
PM-T22
Difference bet. production cycle time and takt time

FR-T23
Ensure that part arrival rate equals service rate (r_a=r_s)
PM-T23
Difference bet. arrival and service rates

DP-T21
Definition or grouping of cust. to achieve ideal range of takt times

DP-T22
Subsystem enabled to meet desired takt time (design and op.)

DP-T23
Arrival of parts at downstream operations according to pitch

Level VI

FR-T221
Ensure that auto. cycle time ≤ minimum takt time
PM-T221
Has this been achieved? (Yes / No)

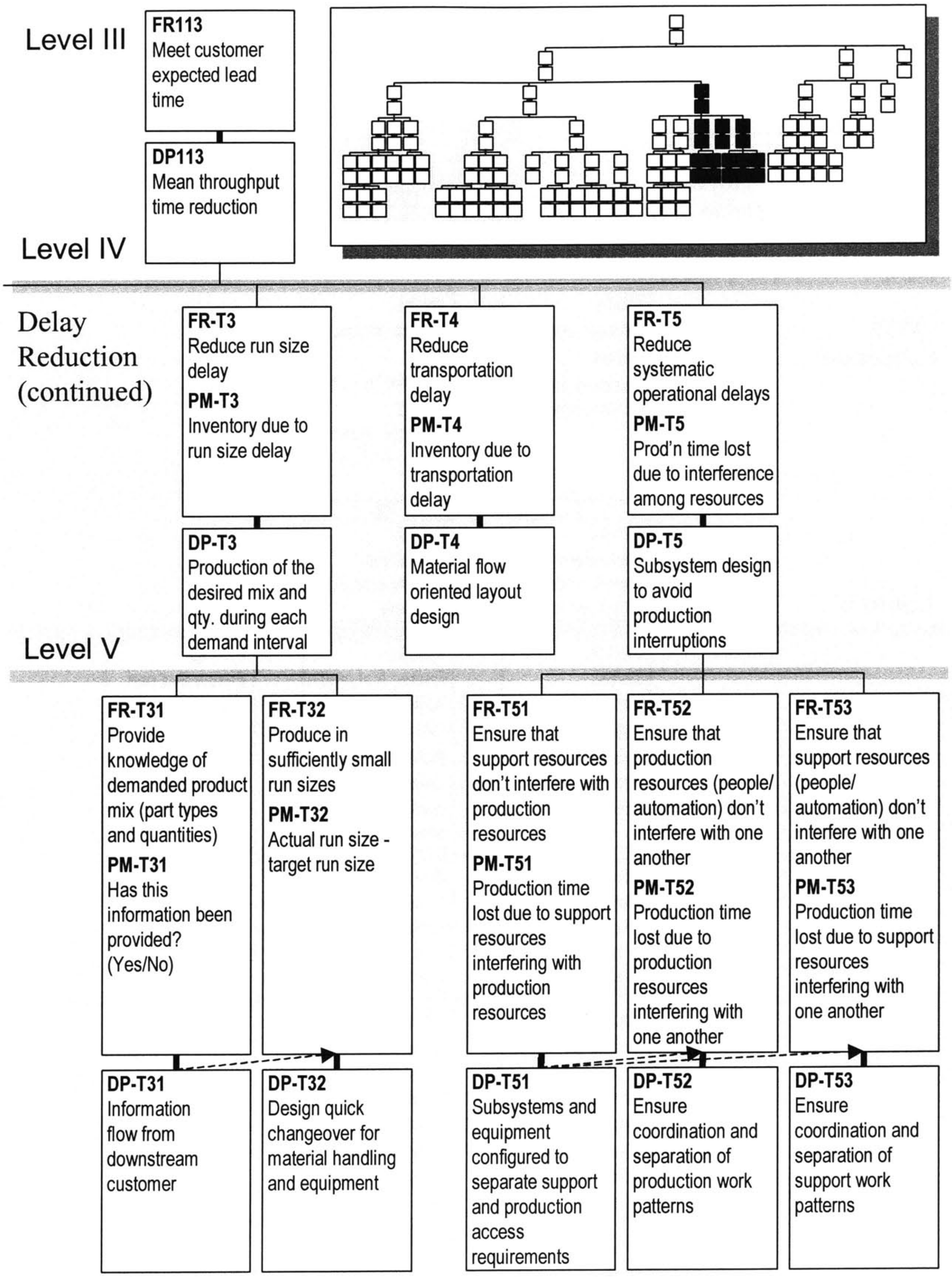
FR-T222
Ensure that manual cycle time ≤ takt time
PM-T222
Has this been achieved? (Yes / No)

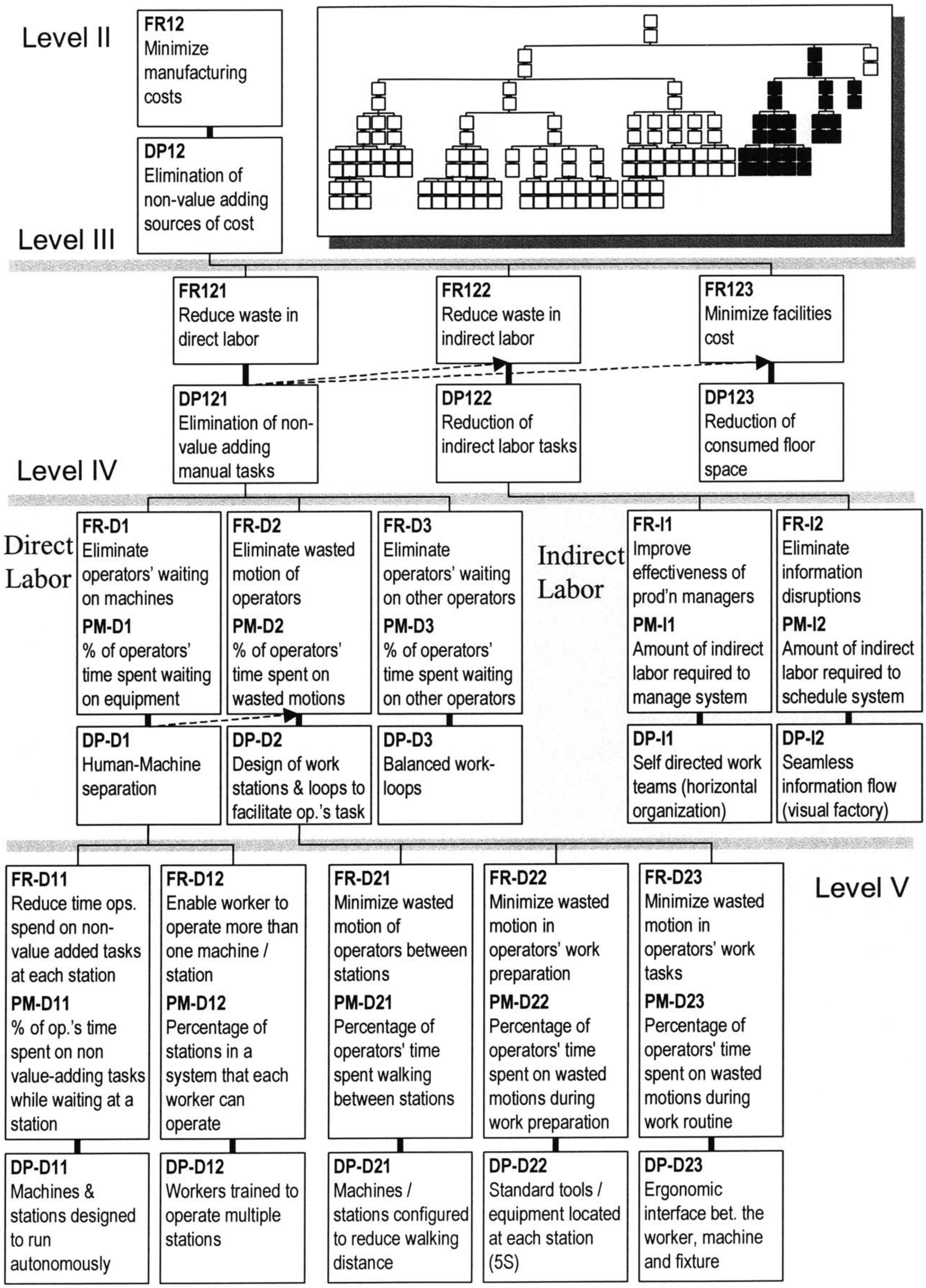
FR-T223
Ensure level cycle time mix
PM-T223
Is average cycle time less than takt time in desired time interval?

DP- T221
Design of approp. auto. work content at each station

DP- T222
Design of approp. operator work content/loops

DP-T223
Stagger prod'n of parts with different cycle times


Level III
FR113
Meet customer expected lead time
DP113
Mean throughput time reduction
Level IV
Delay Reduction (continued)
FR-T3
Reduce run size delay
PM-T3
Inventory due to run size delay
FR-T4
Reduce transportation delay
PM-T4
Inventory due to transportation delay
FR-T5
Reduce systematic operational delays
PM-T5
Prod'n time lost due to interference among resources
DP-T3
Production of the desired mix and qty. during each demand interval
DP-T4
Material flow oriented layout design
DP-T5
Subsystem design to avoid production interruptions
Level V
FR-T31
Provide knowledge of demanded product mix (part types and quantities)
PM-T31
Has this information been provided? (Yes/No)
FR-T32
Produce in sufficiently small run sizes
PM-T32
Actual run size - target run size
FR-T51
Ensure that support resources don't interfere with production resources
PM-T51
Production time lost due to support resources interfering with production resources
FR-T52
Ensure that production resources (people/ automation) don't interfere with one another
PM-T52
Production time lost due to production resources interfering with one another
FR-T53
Ensure that support resources (people/ automation) don't interfere with one another
PM-T53
Production time lost due to support resources interfering with one another
DP-T31
Information flow from downstream customer
DP-T32
Design quick changeover for material handling and equipment
DP-T51
Subsystems and equipment configured to separate support and production access requirements
DP-T52
Ensure coordination and separation of production work patterns
DP-T53
Ensure coordination and separation of support work patterns


Level II
FR12
Minimize manufacturing costs
DP12
Elimination of non-value adding sources of cost
Level III
FR121
Reduce waste in direct labor
FR122
Reduce waste in indirect labor
FR123
Minimize facilities cost
DP121
Elimination of non-value adding manual tasks
DP122
Reduction of indirect labor tasks
DP123
Reduction of consumed floor space
Level IV
Direct Labor
FR-D1
Eliminate operators' waiting on machines
PM-D1
% of operators' time spent waiting on equipment
FR-D2
Eliminate wasted motion of operators
PM-D2
% of operators' time spent on wasted motions
FR-D3
Eliminate operators' waiting on other operators
PM-D3
% of operators' time spent waiting on other operators
Indirect Labor
FR-I1
Improve effectiveness of prod'n managers
PM-I1
Amount of indirect labor required to manage system
FR-I2
Eliminate information disruptions
PM-I2
Amount of indirect labor required to schedule system
DP-D1
Human-Machine separation
DP-D2
Design of work stations & loops to facilitate op.'s task
DP-D3
Balanced work-loops
DP-I1
Self directed work teams (horizontal organization)
DP-I2
Seamless information flow (visual factory)
Level V
FR-D11
Reduce time ops. spend on non-value added tasks at each station
PM-D11
% of op.'s time spent on non value-adding tasks while waiting at a station
FR-D12
Enable worker to operate more than one machine / station
PM-D12
Percentage of stations in a system that each worker can operate
FR-D21
Minimize wasted motion of operators between stations
PM-D21
Percentage of operators' time spent walking between stations
FR-D22
Minimize wasted motion in operators' work preparation
PM-D22
Percentage of operators' time spent on wasted motions during work preparation
FR-D23
Minimize wasted motion in operators' work tasks
PM-D23
Percentage of operators' time spent on wasted motions during work routine
DP-D11
Machines & stations designed to run autonomously
DP-D12
Workers trained to operate multiple stations
DP-D21
Machines / stations configured to reduce walking distance
DP-D22
Standard tools / equipment located at each station (5S)
DP-D23
Ergonomic interface bet. the worker, machine and fixture

APPENDIX B: Differential Case Assembly Fixture

The purpose of this fixture is to facilitate the assembly of the differential case and mistake-proof its operation. This report attempts to present a conceptual idea that will need to be further refined and dimensioned by an equipment supplier. Figure A-0-1 shows the appearance of the fixture.

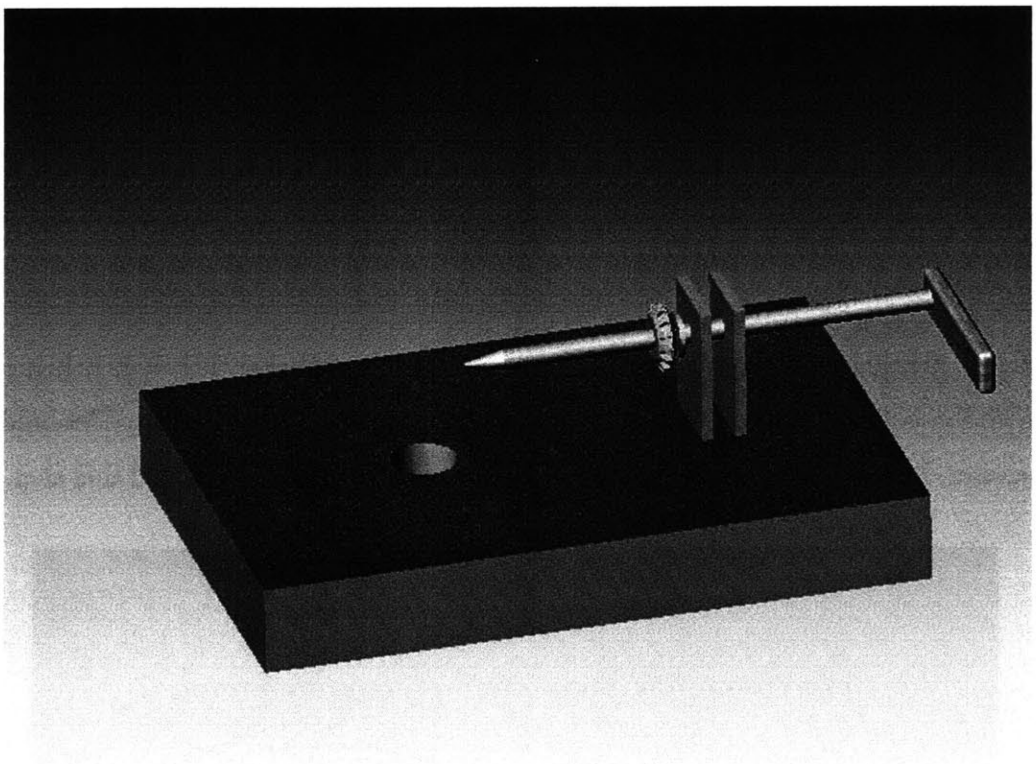


Figure A-0-1: Diff Case Assembly Fixture

The first step in the assembly sequence is to insert the first side gear into the guiding rod (Figure A-0-1). Then, the case casting is positioned in its place and the bottom diff gear is inserted (see .Figure A-0-2).

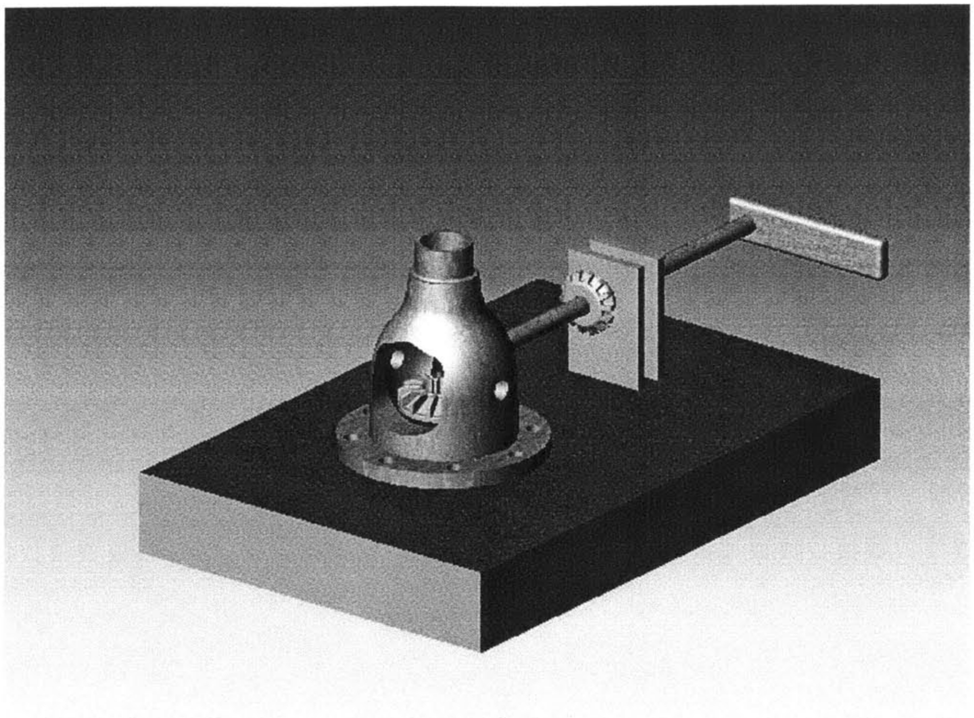


Figure A-0-2: Inserting the bottom diff gear

With the bottom diff gear in place, the top diff gear is inserted and must be held in place by the operator, this should be done with the left hand. Figure A-0-3 illustrated this step.

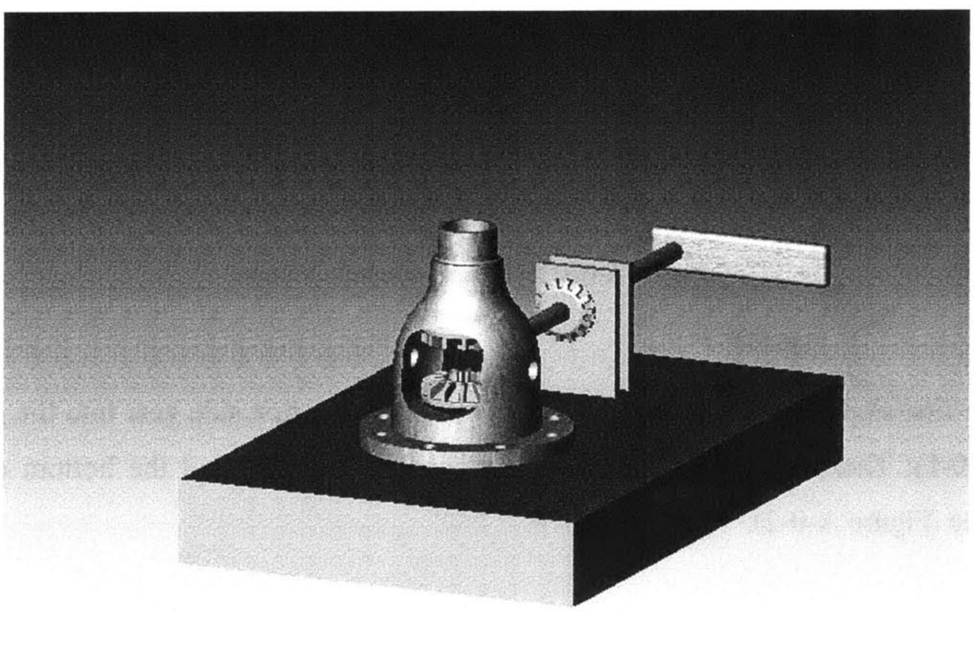


Figure A-0-3: Holding the top diff gear in place

The next step is to pull the guiding rod lever to bring the side gear in. The operator must maintain pressure on the lever in order to hold the top gear in place, which frees his left hand (Figure A-0-4).

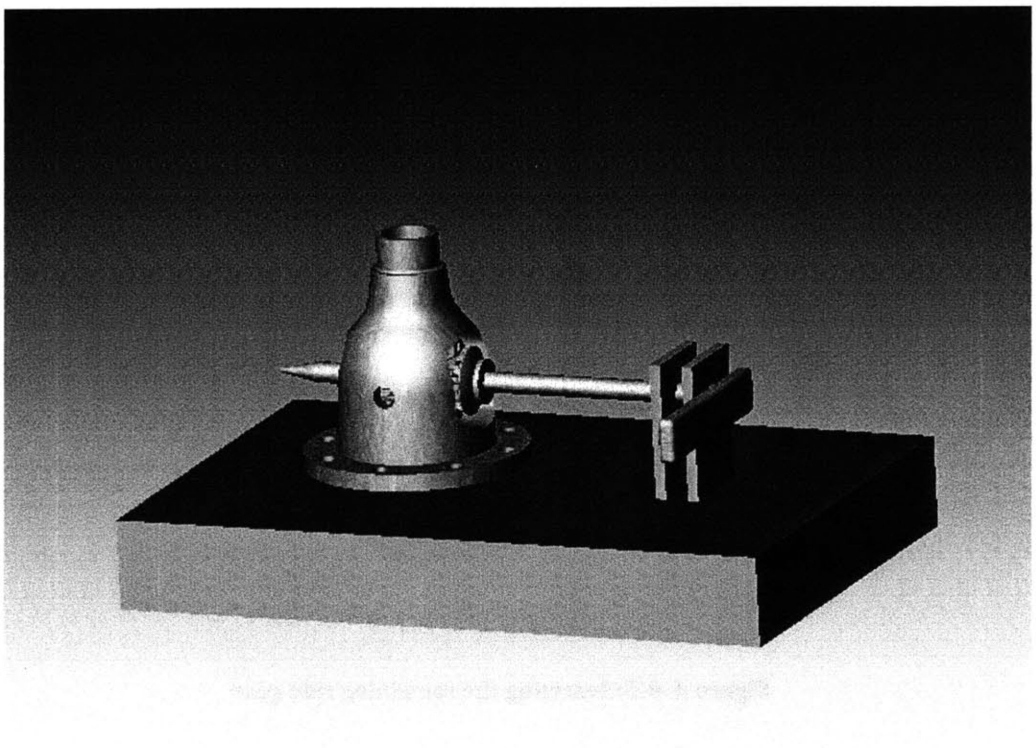


Figure A-0-4: Pulling the guiding rod lever

Now, while still holding the lever, the operator inserts the remaining side gear onto the guiding rod, this ensures proper alignment of the gears. Figure A-0-5 shows the assembly with the side gear already in place. At this stage, the operator holds the gears together with his/her left hand and pulls the guiding rod out of the way with his/her right hand. After this is done, the gears are rotated to their final position and the differential axle is inserted. The only remaining step is to insert the locking pin that holds the axle in place.

The modified standardized work sequence for the operator in this cell is shown in

Table A-1.

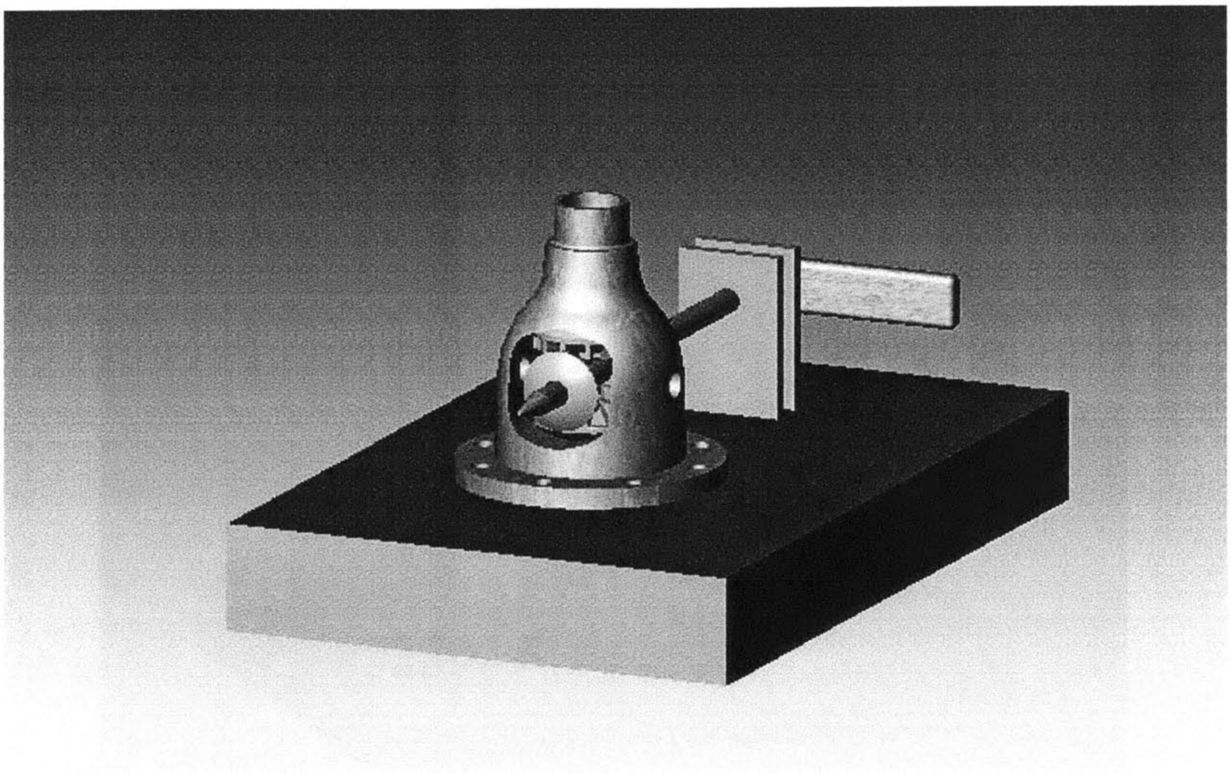


Figure A-0-5: Inserting the remaining side gear

Table A-1: Differential Case Opereator Work Sequence

PROCESS		TIME			
OP#	OPERATION	Man	Walk	Auto	Wait
0	Pick up (1) part from bin	3	1.3	0.0	0
10	Load/Unload (1) part in op 10	5	2.7	112.0	0
10	Gauge op 10 part every 5th cycle	6	2.7	0.0	0
20	Load/Unload (1) part in op 20	5	2.7	117.0	0
20	Gauge op 20 part every 5th cycle	6	4.0	0.0	0
30	Set parts on semi finish part op 30 tray	1	0.0	0.0	0
30	Unload op 30 B Load and set on finish tray	4	0.0	0.0	0
30	Transfer (2) parts from op 30 A load to B load	4	0.0	214.0	105
30	Load (2) parts onto op 30 A load	4	0.0	214.0	0
30	Pick up (1) part from finish op 30 tray	1	1.3	0.0	0
30	Gauge op 30 part every 5th cycle	6	1.3	0.0	0
40	Load/Unload (1) part in op 40	5	6.7	120.0	0
50	Pick up (2) large gears and butter (grease)	3	0.0	0.0	0
50	Pick up (2) small gears and butter (grease)	3	0.0	0.0	0
50	Pick up (2) large washers and place on gears	3	0.0	0.0	0.0
50	Pick up (2) small washers and place on gears	3	0.0	0.0	0.0
50	Place (1) side gear in to fixture guiding rod	1.5	0.0	0.0	0.0
50	Place diff case onto fixture	1.5	0.0	0.0	0.0
50	Place bottom diff gear onto diff case	1.5	0.0	0.0	0.0
50	Place top diff gear onto diff case and hold	2.5	0.0	0.0	0.0
50	Pull guiding rod lever and hold	1.5	0.0	0.0	0.0
50	Insert (1) side gear onto fixture guiding rod	1.5	0.0	0.0	0.0
50	Pull out guiding rod	1.5	0.0	0.0	0.0
50	Rotate gears to final position	2	0.0	0.0	0.0
50	Insert differential axle	4	0.0	0.0	0.0
50	insert locking pin	3	3.0	0.0	0.0
0	place (2) parts on elevator to silo/finish bin	2	2.3	0.0	
	Operator 1 Loop Time: 218. sec.				
	Total	84.5	**28.0**		105.5
	Max. Machine Cycle Time: 218. sec.				
	Cell Cycle Time: 218. sec.				

APPENDIX C: VISTEON RAINBOW CASE CELL PART HANDLING METHOD

General: The associate transfers parts in the production cell in two "loops" or cycles. Each "Loop" results in one completed part.

1st Loop

Procedure for Kasper Horizontal Boring Machine

1. Pick up a part from the incoming raw casting bin with right hand, ensure that the flange is facing towards you.

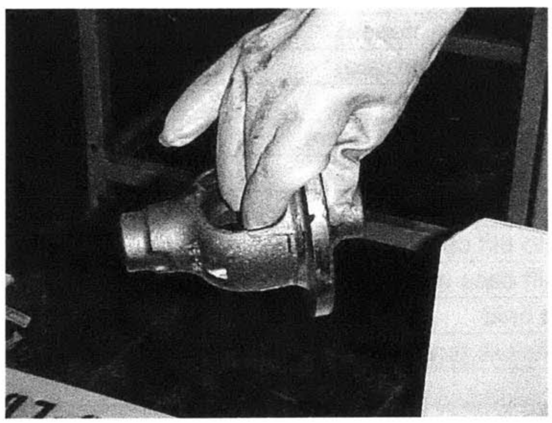


Figure A-0-6: Incoming material

2. Proceed to the Boring machine.
3. When the machine has finished its cycle, unload the finished part with left hand.

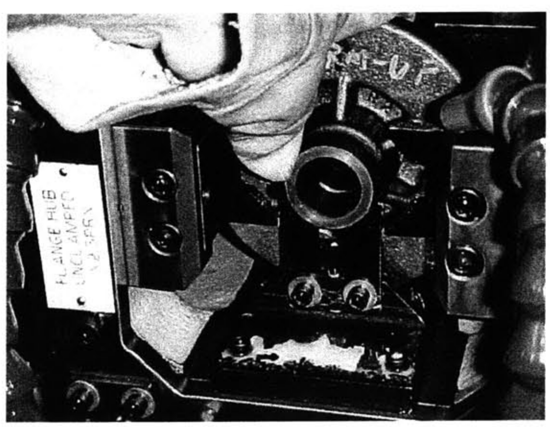


Figure A-0-7: Unload boring machine

4. Make sure there are no chips on the locating surfaces and, with right hand, place raw casting into fixture.

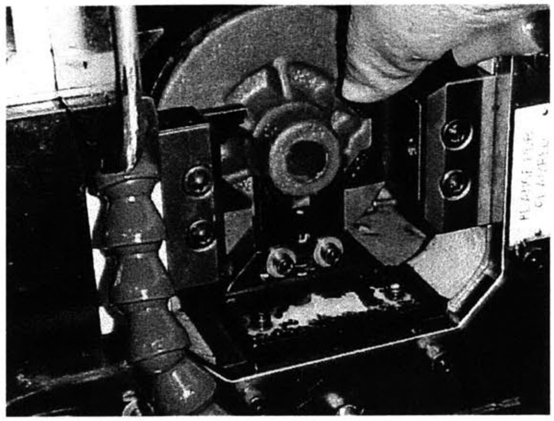


Figure A-0-8: Load boring machine

5. Remove hands and depress door close palm button on right side of machine with right hand to clamp part and close doors.
6. After doors are closed, depress cycle start button on left side of machine to start the machining cycle.
7. Remove any chips from location surfaces on finished Op10 part.
8. Proceed to turning machine, or gage station.

Procedure for Kasper Vertical Turning Machine

1. Place finished Op10 part in part tray.
2. When the machine has finished its cycle, reach into the turning machine with left hand and remove the finished part.

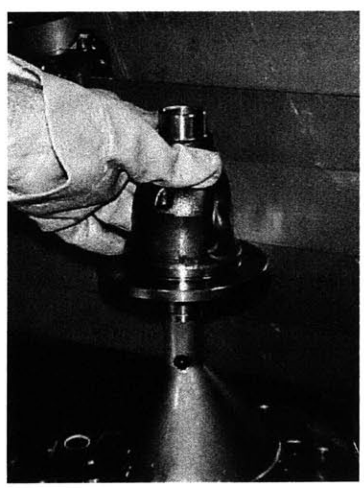


Figure A-0-9: Unload turning machine

3. With right hand make sure there are no chips on the load post or top chuck.
4. With right hand place part from boring machine on load post with flange down.

Figure A-0-10: Load turning machine

5. Remove hands and depress door close palm button on right side of machine with right hand to clamp part and close doors.
6. After doors are closed, depress cycle start button with right hand on left side of machine to start machining cycle.
7. Remove chips from location surfaces on finished Op20 part.
8. Proceed to Horizontal CNC Machining Center.

Procedure for Makino A88 1st Loop

1. Place part in incoming part tray on right side of machine.
2. Pick up a finished part with right hand on left side of machine and proceed to washer.

Procedure for the Ransohoff Parts Washer 1st Loop

1. Place part in one of the empty washer fixtures with flange towards operator.

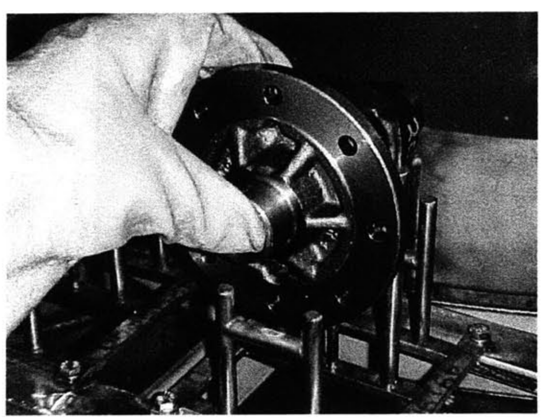


Figure A-0-11: Load washing machine

2. Remove hands and depress cycle start button on left side of machine.
3. With right hand, pick up the part from the finished tray on the left side of machine and proceed to the assembly station.

Procedures for Assembly

1. Operator assembles one part

Figure A-0-12: Assembly station

2. Pick up part and place into the outgoing finished part bin.
3. Proceed to the incoming raw casting bin.

2nd Loop

Procedure for Kasper Horizontal Boring Machine

1. Pick up a part from the incoming raw casting bin with right hand, ensure that the flange is facing towards you.
2. Proceed to the Boring machine.
3. When the machine has finished its cycle, unload the finished part with left hand.
4. Make sure there are no chips on the locating surfaces and, with right hand, place raw casting into fixture.
5. Remove hands and depress door close palm button on right side of machine with right hand to clamp part and close doors.
6. After doors are closed, depress cycle start button on left side of machine to start the machining cycle.
7. Remove any chips from location surfaces on finished Op10 part.
8. Proceed to turning machine, or gage station.

Procedure for Kasper Vertical Turning Machine

1. Place finished Op10 part in part tray.
2. When the machine has finished its cycle, reach into the turning machine with left hand and remove the finished part.
3. With right hand make sure there are no chips on the load post or top chuck.
4. With right hand place part from boring machine on load post with flange down.
5. Remove hands and depress door close palm button on right side of machine with right hand to clamp part and close doors.
6. After doors are closed, depress cycle start button with right hand on left side of machine to start machining cycle.
7. Remove chips from location surfaces on finished Op20 part.
8. Proceed to Horizontal CNC Machining Center.

Procedure for Makino A88 2nd Loop

1. Place the part in the incoming tray on the right side of the machine, there should now be two parts in this tray.
2. Check that the Pallet Ready Button is not lit and that the fixture unclamp cycle is completed.
3. Reach into machine with both hands and grab the flange of the two outside parts and remove them from the fixture by pulling directly towards the operator.

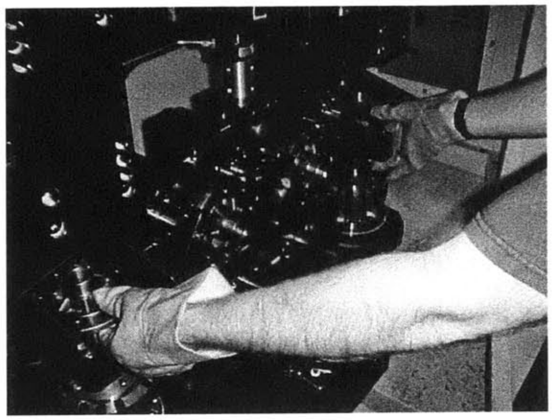


Figure A-0-13: Unload machining center Outside stations

4. Place the two parts in the outgoing work in process tray on the left side of the machine.
5. Remove any chips from location surfaces on the two outside fixture stations.
6. Reach into machine with both hands and remove the two inside parts by pulling directly towards the operator.

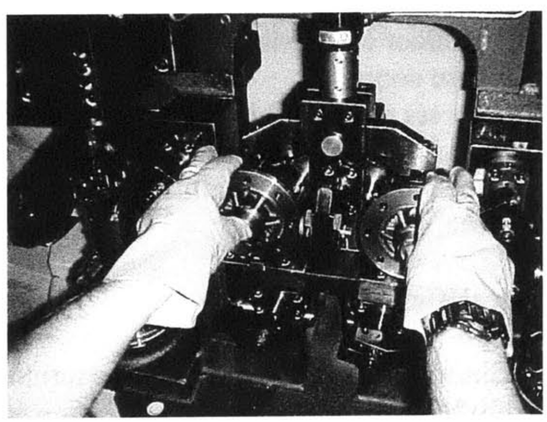


Figure A-0-14: Unload machining center Inside stations

7. Check that location surfaces on the parts are free of chips.
8. Place the parts on the two outside empty fixture position guides by allowing the outside hub to rotate down and resting the part on the load chutes.

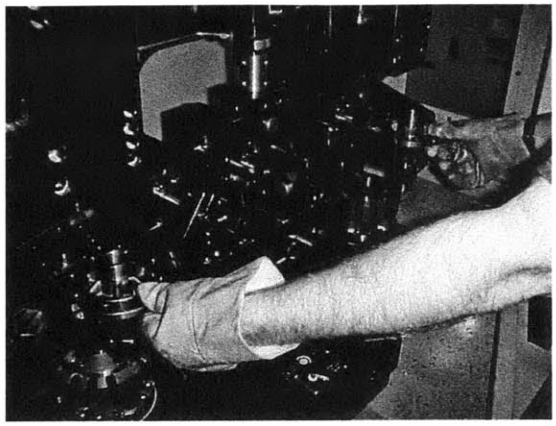


Figure A-0-15: Load machining center Outside stations

9. Push the two parts into the fixture along the load slide until part falls down over the guide pins.
10. Remove any chips from location surfaces on the two inside fixture stations.
11. Pick up the two parts from the incoming work in process bin on the right side of machine and place them into the inside empty fixture positions, hub first with flange closest to the operator.

Figure A-0-16: Load machining center Inside stations

12. Press the parts firmly into the fixture until the flange is flush against the stops.
13. Remove hands and press the cycle start palm button on the left side of the machine.
14. Verify that clamping sequence has completed and part presence check has been performed. The operator panel should look as follows, when complete:

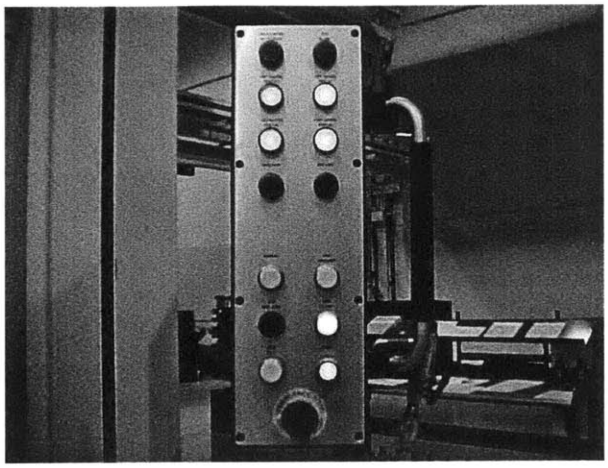


Figure A-0-17: Load machining center Inside stations

15. Pick up one of the two parts in the outgoing work in process bin and proceed to the washer.

Procedure for the Ransohoff Parts Washer 2nd pass

1. Place the part in one of the open fixture positions with the flange towards the operator.
2. Remove both of the finished parts and place them in the outgoing bin to the left of the machine.
3. Pick up one of the parts in the outgoing work in process bin and proceed to the assembly table.

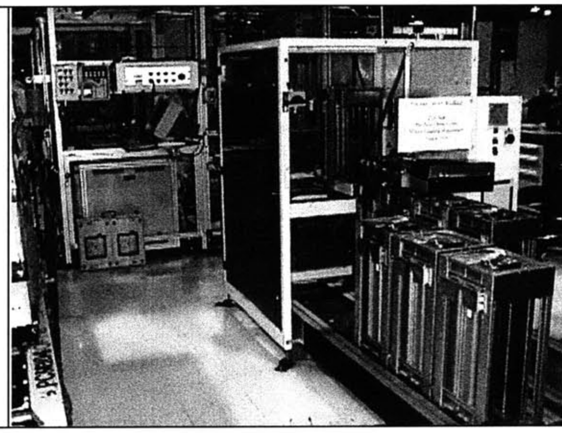
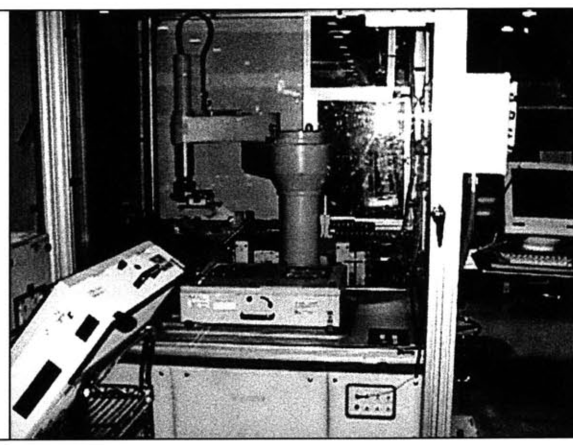
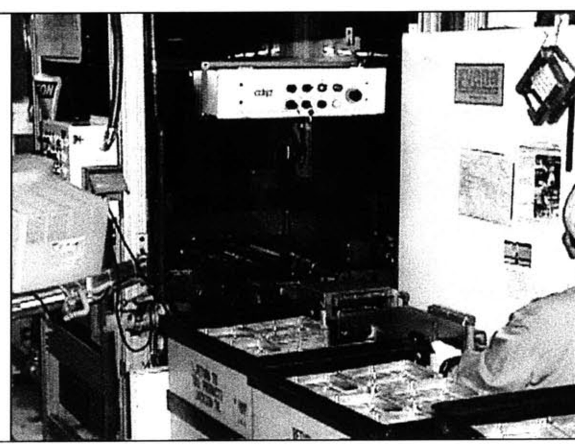
Procedures for Assembly

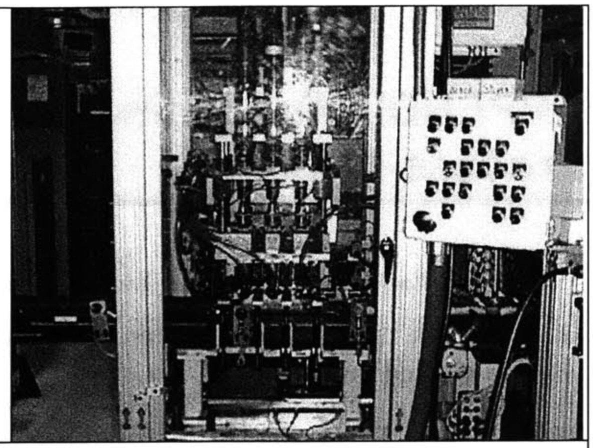
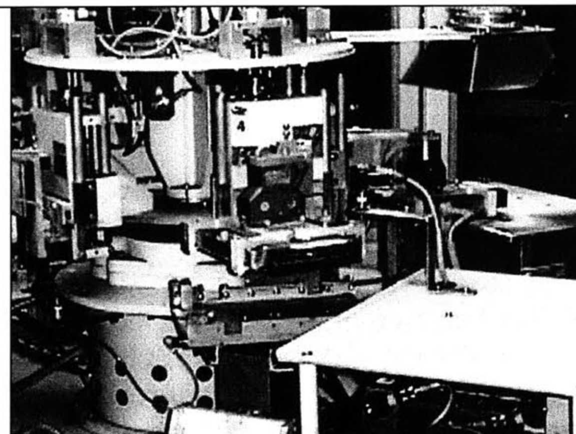
1. Operator assembles one part
2. Pick up part and place into the outgoing finished part bin.
3. Proceed to the incoming raw casting bin and start process from beginning.

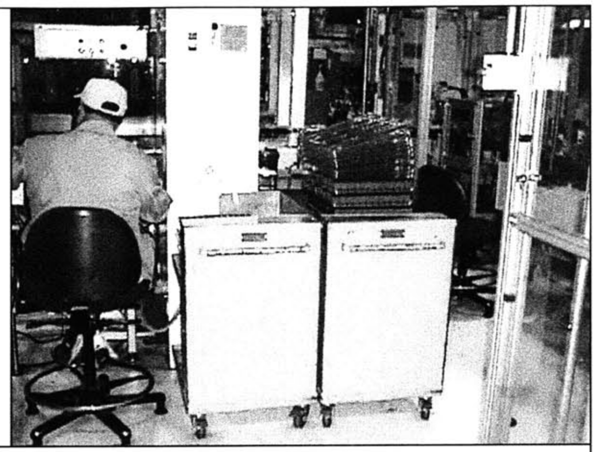
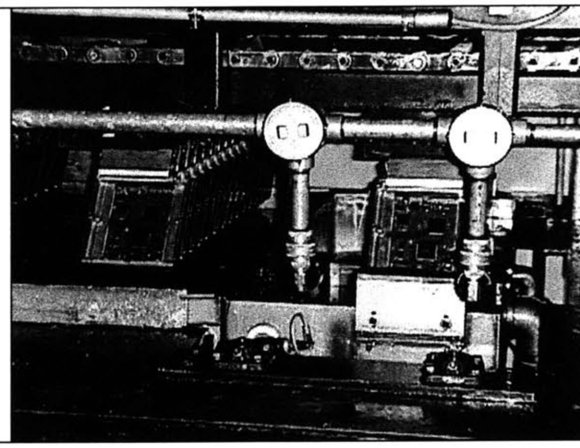
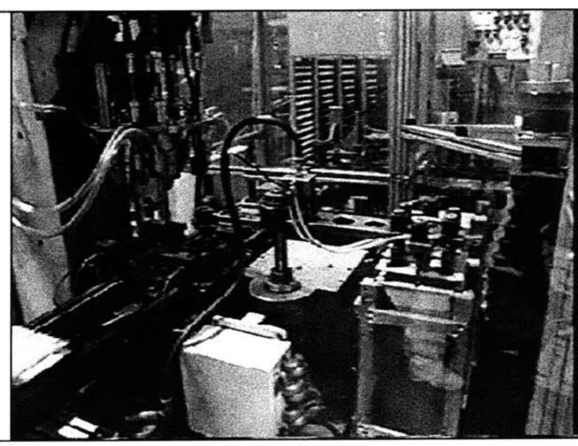
Repeat procedures from the beginning of the 1st Loop

APPENDIX D: Lamination High-speed Line Process steps

Table A-2: Lamination High-speed Line Process Sequence

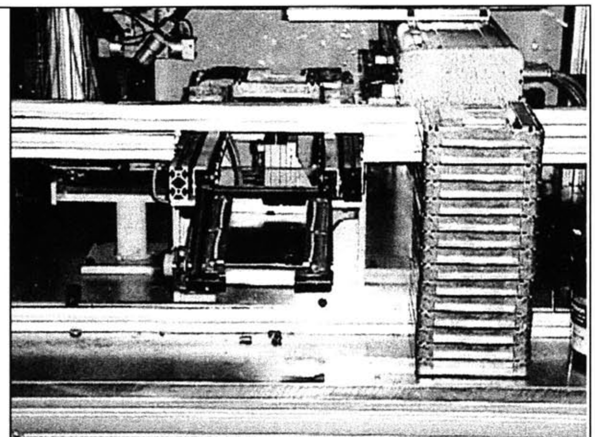
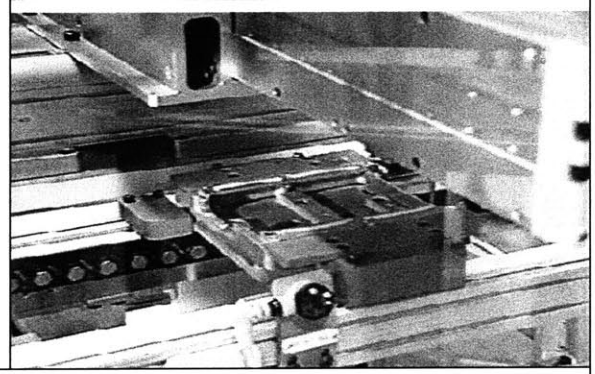
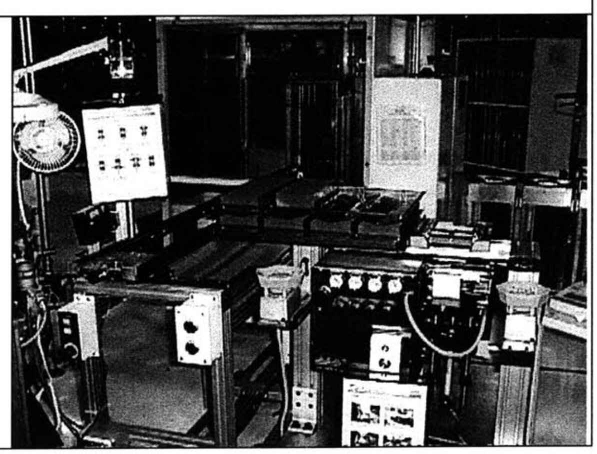
1. Automatic unload of PCBs from the magazines and into the conveyor.	
2. In-circuit test of the PCBs. In the future, this step will take place at the SMD process lines. This step is required to ensure that the necessary components are put in place.	
3. Mating of the PCB with the prepared casting-connector. Previous to this point, an incoming branch delivers the assembled casting-connector. The lamination material has also been applied to this subassembly in preparation for its mating with the PCB.	

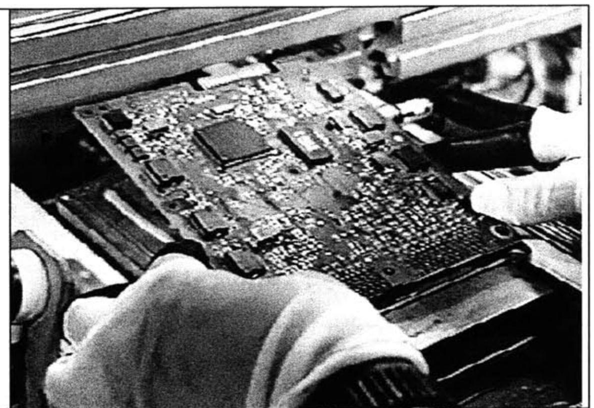
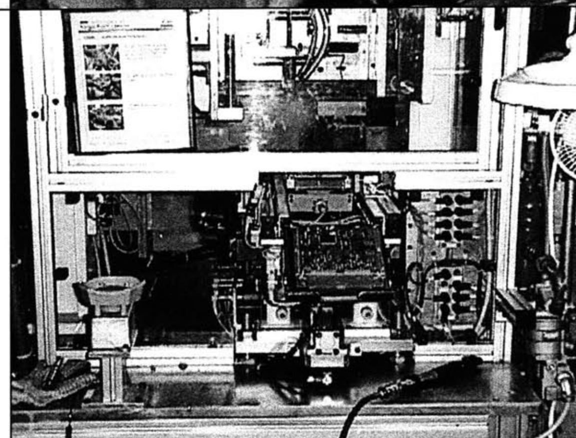
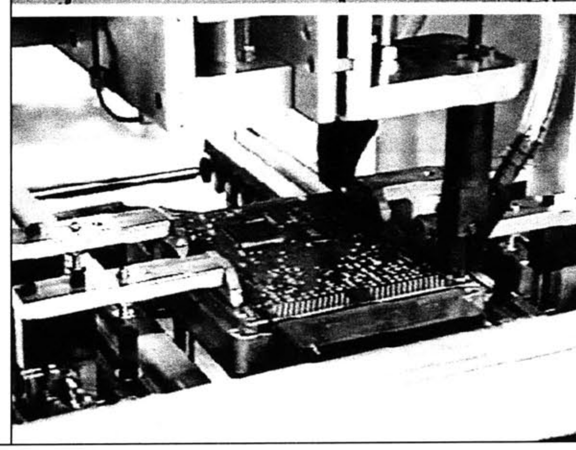
4. Screw board to casting. A six-spindle fully automatic screw-driving machine fastens both components.	
5. Solder connector to board. A rotating machine picks up the boards and dips the connector in a curtain of molten solder.	
6. Bar code reading to identify the PCB family	

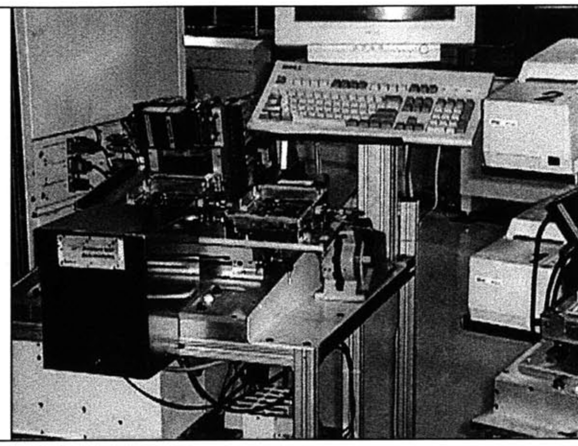
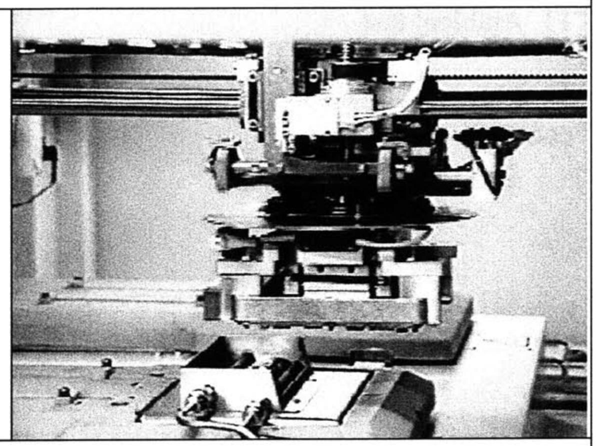
7. Visual inspection for proper solder pattern as well as to detect housing shape integrity.	
8. Voltage-stress-test station	
9. Conformal coating (dip in silicon and oven curing)	
10. Bottom plate placement and attachment with screws	
11. Gasket application (to seal EEC)	
12. Burn-in process to induce failure of weak components	
13. Unload	

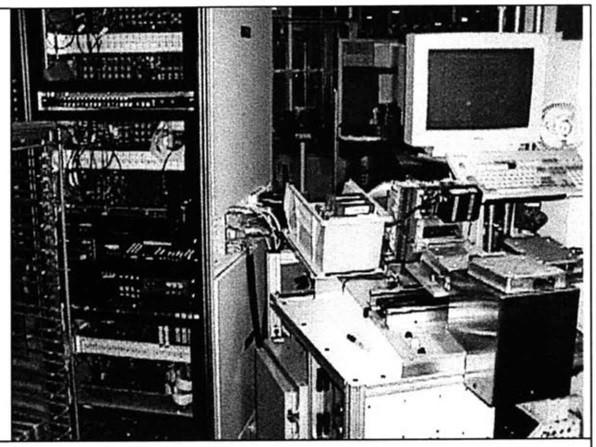
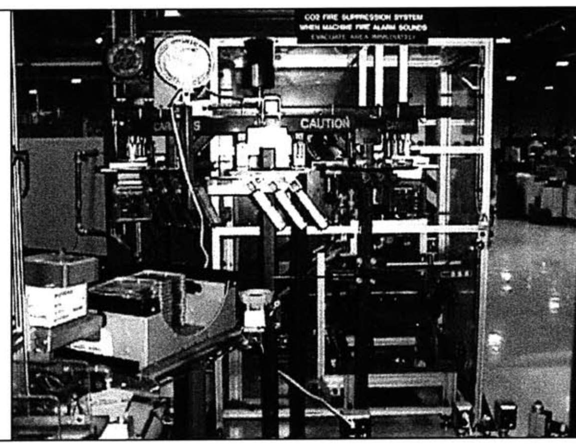
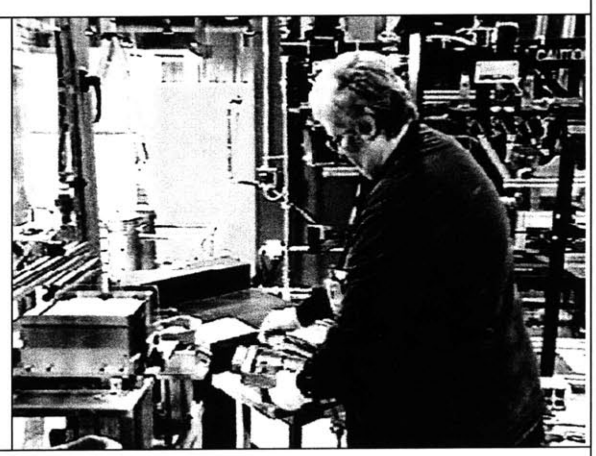
APPENDIX E: Lamination Cell Process steps

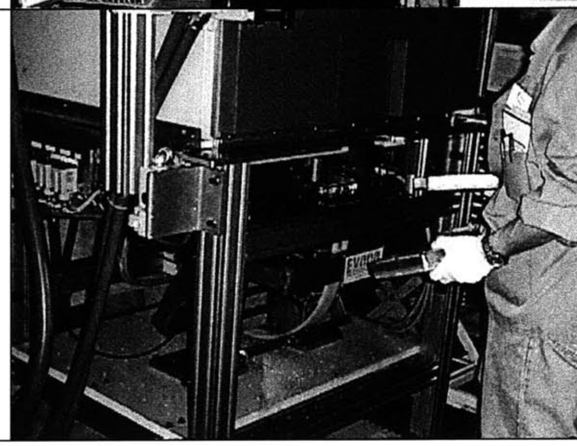
Table A-3: Lamination "Lean" Cell Process Sequence

1. Laminate castings. A similar process to the high-speed line is used. The larger cycle time of the cell allows slower operation and reduced machine complexity.	 
2. Visual inspection for good adhesive beads	
3. Assemble connector to casting (Casting/Connector Assembly Station)	

4. Place PCB onto casting subassembly	
5. Screw-down of PCB into casting subassembly. The larger cycle time of the cell allows a two-spindle machine to be used as opposed to the six-spindle machine at the high-speed line.	 

6. Program input	
7. Solder connector to board	
8. Visual inspection of solder	
9. Native-mode test	

10 Reset test	
11. Ambient test	
12. Dip coat and curing (conformal coating)	
13. Placement of bottom & top cover plates into subassembly	
14. Screw-down cover plates.	(See Step 5)

15. Cold chamber process (batches of 20 parts)	
16. Dry in oven	
17. Hot final test	

APPENDIX F: Work loops for the "lean" cell

Quality Process System Operator Instruction Sheet

Visteon

Product: EEC Process: Manufacturing Operation - EEC Lean Cell

Job ID: Work Cell Operator # 1 of 3

Optional: Tact Time (sec/pc) | Cycle Time (sec/pc)

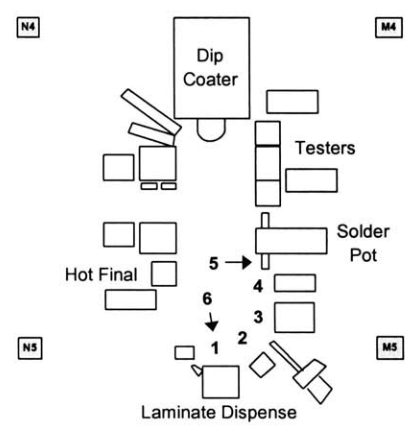
Plant: North Penn Electronics Facility

Rev. Date	Authorized	Rev. Level / Reason
4/5/00	VPS / EEC	0 / Initial
5/2/00	EEC	1 / Operator Feedback

SYMBOL: IN PROCESS STOCK ● | DELTA CRITICAL ▽ | QUALITY CHECK ◇ | QUICK CHANGE OVER QCO | FORD TOTAL PROD. MAINT. FTMP | VISUAL FACTORY | ERROR PROOFING | OTHER | JSA

Step #	Work Steps	Optional Area	Possible Health & Safety Hazards	Recommended Job Procedures file: lean_***.ppt
1	Walk to front of Laminate Dispense machine. While taking casting from tote with right hand, use left hand to remove finished casting with laminate. While placing new casting on machine conveyor with right hand, use left hand to place and position casting with laminate into connector to casting nest. Visually inspect for good adhesive beads.			lam dispense lam bead inspect
2	Walk to front of Connector to Casting machine, and with left hand, take a connector from the tray and place it over the edge of the casting. Activate the machine by placing both hands on the palm switches. After waiting for cycle to finish, pick up finished casting with connector with right hand. Either check to ensure board label matches bar code label, or make sure machine scanner did not fault.			casting to connect grohman stacklight2
3	Walk to Board Screwdown machine. Place casting with connector on conveyor. Pick up the panel with right hand and use both hands to carefully place board over casting. Place hand over palm switch. Pick up completed module from tray with right hand.			board screwdown board handling
4	Walk to Programmer. When in front of machine, check computer screen to ensure previous module did not fail. Then, pick up completed module with left hand and use right hand to place new module in machine fixture (pins facing you and label facing up). For TGA modules, reference "lean_TGAflow.ppt"			TGAflow.ppt
5	Transfer module to right hand. Turn towards Solder Pot and use right hand to place module on machine conveyor, with label facing up and connector pins facing forward (going in first).			selective solder
6	Repeat loop from step 1.			
	NON-REPETITIVE TASKS If not done by material handler, update schedule daily and load/unload grohmann. If not done by mechanic, load board screwdown screw-bowls.			

EEC LEAN CELL



QPS Sheet #: 1 of 1

Zone: EEC Department #: 5741

Sign-off / Reps	Shift Code 1	Shift Code 2	Shift Code 3
Operators			
Workgroup Leader			
Supervisor			
Health & Safety			
Maintenance			
Engineering			

SAFETY EQUIPMENT

SAFETY LOCKS	EYE PROTECTION	FOOT PROTECTION	HAND PROTECTION	HEARING PROTECTION	HARD HAT	RESPIRATOR	APRON	SMOCK	GROUND STRAP OR HEEL STRAP
☐	☒	☐	☒	☐	☐	☐	☐	☒	☒

Visteon

Quality Process System Operator Instruction Sheet

Product: EEC Process: Manufacturing Operation - EEC Lean Cell

Job ID: Work Cell Operator # 2 of 3

Optional: Tact Time (sec/pc)	Cycle Time (sec/pc)

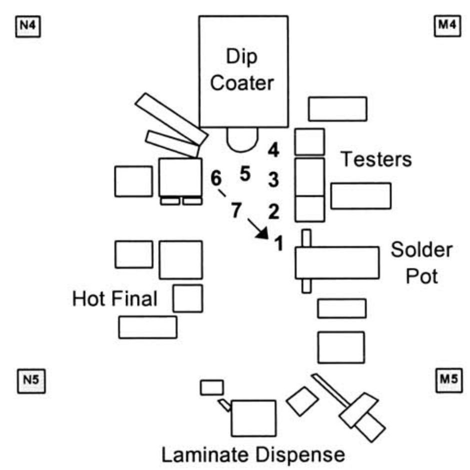
Plant: North Penn Electronics Facility

Rev. Date	Authorized	Rev. Level / Reason
4/5/2000	VPS / EEC	0 / Initial
5/2/00	EEC	1 / Operator Feedback

IN PROCESS STOCK	DELTA CRITICAL	QUALITY CHECK	QUICK CHANGE OVER	FORD TOTAL PROD. MAINT.	F T M P	VISUAL FACTORY	ERROR PROOFING	OTHER	JSA
●	▽	◇	QCO						GRASP

Work Steps	Optional Area	Possible Health & Safety Hazards	Recommended Job Procedures file: lean_***.ppt
Note: for tester reject procedure, reference "fail_pro.ppt"			selective solder
Walk to post-Solder Pot queue. Pick up module off conveyor with right hand and lift it to magnifying glass for Solder Inspection, bottom side up. Hold with both hands during inspection. Inspect to ensure that all solder joints have sufficient solder, as shown by the posted visual aid. ◇			
Turn toward Native Mode tester and look to ensure the green light is on next to module that has finished testing. Take the finished module out of the fixture with right hand and place the new module in that fixture with left hand.			
Step toward Resets tester and look to ensure the green light is on next to module that has finished testing. Take the finished module out of the fixture with left hand and place the new module in that fixture with right hand.			
Step toward Ambient tester and use right hand to remove module that has finished testing from fixture, making sure that the module did not fail (by looking at fixture lights). Then place the new module in the available fixture space.			
Turn toward Dip Coater and insert module that is in right hand into the back-most available slot (furthest left) of the three under the LOAD sign. Next, step toward UNLOAD sign and slide out (pull) the front-most slot (furthest right) module. After all three LOAD slots are filled, all three UNLOAD slots are empty, and red light is flashing, place right hand over palm switch to activate conveyor.			
Transfer module to right hand. Take bottom cover with left hand and place module over it, afterwards holding the assembly with left hand. With right hand, use magnet to slide and position top cover onto top of module. Pick up completed assembly with right hand, and place new assembly onto screwgun machine conveyor with left hand. Inspect completed module for six fully-seated screws and (after transferring module to left hand) stack good (completed) modules, five high, on pre-inspect table next to cold chamber. Use both hands over palm switches to activate machine. ●			
Repeat Cycle – Walk to back-end of Solder Pot.			

EEC LEAN CELL



SAFETY LOCKS	EYE PROTECTION	FOOT PROTECTION	HAND PROTECTION	HEARING PROTECTION	HARD HAT	RESPIRATOR	APRON	SMOCK	GROUND STRAP OR HEEL STRAP
☐	☒	☐	☒	☐	☐	☐	☐	☒	☒

QPS Sheet #: 1 of 1

Zone: EEC Department #: 5741

Sign-off / Reps	Shift Code 1	Shift Code 2	Shift Code 3
Operators			
Workgroup Leader			
Supervisor			
Health & Safety			
Maintenance			
Engineering			

APPENDIX F

Visteon

Quality Process System Operator Instruction Sheet

Product: EEC Process: Manufacturing Operation - EEC Lean Cell

Job ID: Work Cell Operator # 3 of 3

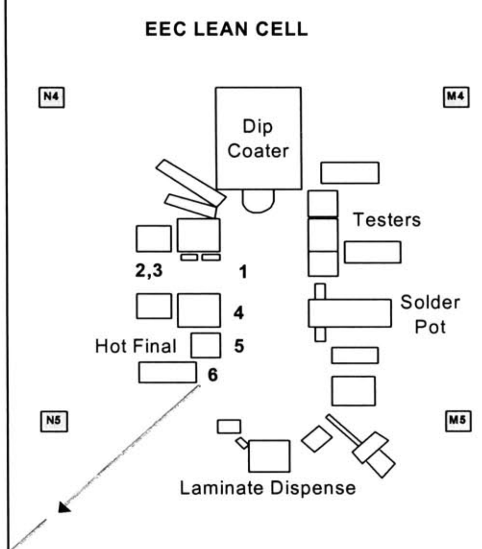
Optional: Tact Time (sec/pc)	Cycle Time (sec/pc)

Plant: North Penn Electronics Facility

Rev. Date	Authorized	Rev. Level / Reason
4/5/00	VPS / EEC	0 / Initial
5/2/00	EEC	1 / Operator Feedback
5/16/00	EEC	2 / Hot Final Added

SYMBOL	IN PROCESS STOCK	DELTA CRITICAL	QUALITY CHECK	QUICK CHANGE OVER QCO	FORD TOTAL PROD. MAINT.	F T M P	VISUAL FACTORY	ERROR PROOFING	OTHER	JSA
	●	▽	◇							

Step #	Work Steps	Optional Area	Possible Health & Safety Hazards	Recommended Job Procedures lean_***.ppt
1	Inspect all pre-cold chamber modules, one at a time, to ensure each module is free of visible defects, especially checking that 6 screws are present and completely seated. Also, gently slide your finger into the J3 connector opening (opposite the connector pins) to ensure conformal coating is present. After visual inspection is complete, stack the modules 5 high on the post-inspect table. BE CAREFUL NOT TO MIX UNINSPECTED MODULES WITH MODULES READY FOR THE COLD CHAMBER!!! When the next set of modules is ready, they are ready to be loaded into a chamber. ◇			
2	When the units are ready to be taken out of the chamber, BE SURE TO WEAR INSULATED GLOVES. Take the modules out of the chamber and place them on the oven cart. Close the chamber door and push the cart of cold modules to the near side of the oven.			
3	After a cold chamber is empty, load the chamber, oriented so that the modules' connectors are facing away from the chamber's condensor. Try to keep the chamber door open for a minimal amount of time to keep the chamber cold. Take turns between the two chambers.			
	Note: defrost cold chambers each shift as described in "lean_defrost.ppt"			defrost
4	Occasionally, check to see if the oven is at least 100 degrees C. When the "HOT PART PRESENT" light is on, MAKE SURE YOU ARE WEARING HEAT-RESISTANT GLOVES BEFORE TOUCHING A HOT MODULE!!! Open the oven's sliding door and remove the hot module with your left hand, placing it on the appropriate tray to the left of the oven. Insert a cold module in the slot with your right hand and slide close the door. Place your right hand over the sensor to cycle the oven elevator (if desired, this can be done at the beginning of step 4). Repeat cycle.			
5	Step toward Hot Final tester and use right hand to remove module that has finished testing from fixture, making sure that the module did not fail (by looking at fixture lights). Then place the new module in the available fixture space. The tested module then can be placed on the appropriate cart.			
6	Once full, the cart of post-test modules (on trays) can be taken to the transfer line to be loaded prior to the gasket install station. Be sure to warn the operators in the area that the parts on the cart are very hot!			
	NON-REPETITIVE TASKS (other than chamber defrost) If not done by mechanic, load cover assembly screw-bowls.			



QPS Sheet #: 1 of 1

Zone: EEC Department #: 5741

Sign-off / Reps	Shift Code 1	Shift Code 2	Shift Code 3
Operators			
Workgroup Leader			
Supervisor			
Health & Safety			
Maintenance			
Engineering			

SAFETY EQUIPMENT	SAFETY LOCKS	EYE PROTECTION	FOOT PROTECTION	HAND PROTECTION	HEARING PROTECTION	HARD HAT	RESPIRATOR	APRON	SMOCK	GROUND STRAP OR HEEL STRAP
	☐	☒	☐	☒	☐	☐	☐	☐	☒	☐

APPENDIX G: MSDD Evaluation of the Manufacturing Systems

Functional Requirements - Quality	Mass Line	Cell
FR Q 11 - Eliminate machine assignable causes	0	0
FR Q 121 - Ensure that operator has knowledge of required tasks	1	1
FR Q 122 - Ensure that operator consistently performs tasks correctly	0	1
FR Q 123 - Ensure that operator human errors do not translate to defects	0	1
FR Q 13 - Eliminate method assignable causes	1	1
FR Q 14 - Eliminate material assignable causes	0	0
FR Q 2 - Center process mean on the target	1	1
FR Q 31 - Reduce noise in process inputs	0	0
FR Q 32 - Reduce impact of input noise on process output	0	0
Functional Requirements - Identifying and resolving problems		
FR R 111 - Identify disruptions when they occur	0	1
FR R 112 - Identify disruptions where they occur	0	1
FR R 113 - Identify what the disruption is	1	0
FR R 121 - Identify correct support resources	0	0
FR R 122 - Minimize delay in contacting correct support resources	0	0
FR R 123 - Minimize time for support resource to understand disruption	0	0
FR R 13 - Solve problems immediately	0	1
Functional Requirements - Predictable output		
FR P 11 - Ensure availability of relevant production information	1	1
FR P 121 - Ensure that equipment is easily serviceable	0	1
FR P 122 - Service equipment regularly	0	1
FR P 131 - Reduce variability of task completion time	0	0
FR P 132 - Ensure availability of workers	1	1
FR P 133 - Do not interrupt production for worker allowances	0	1
FR P 141 - Ensure that parts are available to the material handlers	1	1
FR P 142 - Ensure proper timing of part arrivals	1	1
Functional Requirements - Delay Reduction		
FR T 1 - Reduce lot delay	0	1
FR T 21 - Define takt time(s)	0	1
FR T 221 – Ensure that automatic cycle time <= minimum takt time	0	1
FR T 222 - Ensure that manual cycle time <= takt time	0	1
FR T 223 - Ensure level cycle time mix	0	1
FR T 23 - Ensure that part arrival rate is equal to service rate	0	1
FR T 31 - Provide knowledge of demanded product mix (part types and quantities)	0	0
FR T 32 - Produce in sufficiently small run sizes	0	0
FR T4 - Reduce transportation delay	1	1
FR T 51 - Ensure that support activities don't interfere with production activities	0	1
FR T 52- Ensure that production activities don't interfere with one another	0	1
FR T 53 - Ensure that support activities (people/automation) don't interfere with one another	1	1
Functional Requirements - Operations Cost		
FR D 11 - Reduce time operators spend on non-value added tasks at each station	0	1
FR D 12 - Enable worker to operate more than one machine / station	0	1
FR D 21 - Minimize wasted motion of operators between stations	0	1
FR D 22 - Minimize wasted motion in operators' work preparation	1	1
FR D 23 - Minimize wasted motion in operators' work tasks	0	1
FR D 3 - Eliminate operators' waiting on other operators	0	1
FR I 1 - Improve effectiveness of production managers	0	1
FR I 2 - Eliminate information disruptions	0	0
FR 123 - Minimize facilities cost	0	1
FR 13 – Minimize investment over production system lifecycle	0	1