Equipment Design Framework and Tools to Support Production System Design

by

Deny Daniel Gomez

B.S. Engineering
Harvey Mudd College, 1998

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2000

Signature of author.................................
Department of Mechanical Engineering
May 5, 2000

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

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

Equipment Design Framework and Tools to Support Production System Design

by

Deny Daniel Gomez

Submitted to the Department of Mechanical Engineering
on May 5th, 2000 in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering

ABSTRACT

This thesis will focus on the design and operation of the equipment in manufacturing enterprises with the intention of having the equipment support the design of the production system and the achievement of the high-level enterprise objectives. Competitiveness in today's business environment requires the use of a structured approach to ensure that a company's production system is designed to achieve its business objectives, and all too often production systems are designed without regard to such objectives. An effective approach to establish the connection between the elements of a production system and the business objectives of an enterprise is the Manufacturing System Design Decomposition (MSDD) developed by the Production System Design Laboratory at MIT and introduced in this thesis. The MSDD uses Axiomatic Design methodology to identify the thought process behind *what* a production system intends to achieve and *how* it intends to achieve it. A subset of the Functional Requirements identified by the MSDD relates to the design and operation of equipment, and this thesis will identify that subset and discuss how the application of such requirements can lead to the design and use of equipment to enable the production system to achieve its high-level goals. This thesis will also introduce the Equipment Evaluation Tool, which can be used to assess how well the design and operation of a particular piece (or set) of equipment supports the production system design. The Equipment Evaluation Tool identifies which physical characteristics the equipment should have to satisfy the Functional Requirements from the MSDD associated with equipment design and operation. Finally, this thesis will discuss a case study of the application of the equipment design framework and the Equipment Evaluation Tool. The case study centers on a project for the concept-level design of equipment for the final assembly of automotive steering gears. The case study illustrates how equipment designed using the equipment design framework and the Equipment Evaluation Tool can, when compared to equipment designed in a traditional fashion, better enable manufacturing enterprises to achieve their high-level objectives.

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

Acknowledgments

There is a large number of people that I want to thank for their contributions not only for the completion of this thesis but also for supporting me to pursue my goals and dreams and for making my life much more enjoyable. Since so many people have touched my life I am sure to forget at least a few of you, but if you know me then you know that I have a bad memory so please forgive me.

I have to start with my family, that core of supportive people that have always been there for me and that have seen me grow not only physically but also as a person and have accompanied me through the good times and the bad. My wonderful mother Virginia, always involved with everything that happens in the family, always with a smile on your face and always so willing to give love and to sacrifice yourself for the well being of those of us who have the pleasure of being the recipients. My equally wonderful father Pedro, such a great example of integrity and strong moral values, I cannot imagine who I would be without you as a role model and great father. My beloved sister Danybel, the happiest woman with the best character that I've ever met, thank you for putting up with me for all those years. And the newest member of our family, my niece Daniela, such a happy, energetic and smart kid that she brings the entire family together.

Then there is my "second family", la familia Morchain, a group of wonderful people that happen to be related to each other. My best buddy Daniel, a special compadre that I cannot thank enough for the great times we have spent together and the ones that are to come. Alicia, you still own a big piece of my heart and I could not ask for more love from anyone. And Señora Liliana, thank you for being my second mother and for accepting me as part of your family.

My friends from Caracas are the most special group of people that I cannot thank enough for all the great times we have spent together. My best friend Rafael, we've been soul mates for 20 years and counting, you are truly my brother. My cousin Carlos, my cousin Marvic, Tía Josefina y Caracciolo, who make the oddest yet most fun family I know. My friends Noelia, Marcos, Alexandra and Luis Eduardo, thanks for the good times.

From Harvey Mudd I have to thank the people who made it really special for me. Nandan, Matt, Ken and Carl, we spent so many hours working and having fun together that the college years seemed to go by really fast. And Allison, you are a really special girl, I love your innocence and your genuine personality.

I want to thank my buddies from grad school whom I have had a lot of fun with also. Thanks to Charlie, for making life at home fun. Thanks to Carlos, Memo and Cesar, my Latin friends who give Boston a flavor of home. Thanks to everyone at the PSD lab: Dan, Jim, Jorge, Jose, Ania, Alex, Yong-Suk, Jochen, Jongyoon, Abhinav and Brandon. And thanks to past members: Richard, Carlos, Micah, Andrew and Kristina; and to our many visiting students who have contributed to our discussions and work.

Finally I want to thank Prof. David Cochran for all his guidance and advice, and also Pat for always lending a helping hand. I also want to thank the folks at Visteon Indianapolis who contributed to my work: Bill Ramirez, Jeff Clark, Greg Fisher, Steve Watkins and Stuart Anderson.

Table of Contents

List of Figures

List of Tables

Introduction

This thesis will focus on the design and operation of the equipment in a manufacturing enterprise. The objective is to introduce a framework and a tool for the design and operation of the equipment so that it supports the design of the production system and the achievement of the high-level enterprise objectives.

Competitiveness in today's business environment requires the use of a structured approach to ensure that a company's production system is designed to achieve its business objectives. Even today, manufacturing ventures often design their production systems without regard to such high-level objectives. An effective approach to establish the connection between the elements of a production system and the business objectives of an enterprise is the Manufacturing System Design Decomposition (MSDD) developed by the Production System Design Laboratory at MIT and introduced in this thesis. The MSDD uses Axiomatic Design methodology to identify the thought process behind *what* a production system intends to achieve and *how* it intends to achieve it.

The equipment is a critically important element of any production system, and as such it is important to ensure that the design and operation of the equipment supports the objectives that drive the design of the production system. A subset of the Functional Requirements identified by the MSDD relates to the design and operation of equipment. This thesis will identify that subset and discuss how those requirements can be the basis of a framework to design equipment that enables the production system to achieve its high-level goals. Also, this thesis will introduce the Equipment Evaluation Tool, which can be used to assess how well the design and operation of a particular piece (or set) of equipment supports the production system design. In short, the main focus of this work is to provide a framework and an evaluation tool to guide the design of equipment to enable the enterprise to achieve its high-level objectives.

Finally, this thesis will discuss a case study of the application of the equipment design framework and the Equipment Evaluation Tool. The case study centers on a project for the concept-level design of equipment for the final assembly of automotive steering gears. The case study illustrates how equipment designed using the equipment design framework and the Equipment Evaluation Tool can, when compared to equipment designed in a traditional fashion, better enable manufacturing enterprises to achieve their high-level objectives.

Chapter Summaries

Chapter 1: The Production System Design Framework

This chapter introduces the Production System Design (PSD) framework developed by the Production System Design Laboratory at the Massachusetts Institute of Technology. The chapter explains the concepts of the Toyota Production System, also known as *lean production*. The Toyota Production System is a set of methods for designing, operating and controlling a production system that have the ultimate objective of eliminating waste in all its forms from the system. Lean production follows two fundamental principles: Just-In-Time and autonomation (or man-machine separation), which together with a set of common sense tools and ideas leads to a responsive manufacturing system that can accurately satisfy customer demand in short lead-times, while maintaining high quality, low inventories and minimal costs. The chapter also introduces Axiomatic Design, a methodology that provides a scientific base for design. Axiomatic Design is a process of making decisions about *what* a design intends to achieve (Functional Requirements) and *how* it intends to achieve it (Design Parameters).

The PSD framework applies Axiomatic Design methodology to the design of a production system to define its objectives (the what's) and the corresponding physical implementations (the how's). Using Axiomatic Design for the design of production systems leads to designs that are simple, easy to operate and that achieve business objectives. The PSD framework identifies the thought process and the key decisions that need to be made during the design of a production system, and it serves as a method to communicate those decisions to the people in an organization. The PSD framework encapsulates the knowledge from the Toyota Production System literature and experience in such a way that a system designed using the PSD framework will achieve the principles of lean production.

Chapter 2: Equipment Design and the Production System Design Framework

The MSDD communicates the system requirements to the designers of subsystems, and of particular interest in the scope of this thesis are the requirements placed on the design of equipment. This chapter presents a summary of the equipment design framework developed by Arinez and Cochran to design equipment that meets the requirements of the production system identified by the PSD framework [Arinez, 2000; Arinez and Cochran, 1999; Arinez et al., 1999]. A subset of the FRs and DPs identified by the MSDD affect the design of equipment, and that subset serves as the basis for a framework for the design of equipment that achieves the requirements of the system.

A twofold framework is presented, following the structure of the work by Arinez and Cochran. The first method consists in the identification of the subset of FRs/DPs from the MSDD that affect equipment design, and the further use of those requirements to elaborate guidelines to be supplied to the equipment designers. These guidelines build on the requirements from the MSDD and include specific information on the mechanical, electrical and other relevant physical properties that the equipment must have to achieve the system requirements. The second method involves the direct application of Axiomatic Design methodology to the design of equipment by developing an Equipment Design Decomposition (EDD). In this method, a link is established between the EDD and the MSDD in which the process of decomposition of the EDD is guided by the system requirements from the MSDD. This link ensures that the EDD provides a detailed description of the physical properties of the equipment to achieve the system requirements from the MSDD.

Chapter 3: Equipment Evaluation Tool

This chapter presents an Equipment Evaluation Tool that can be used to assess how well the design and operation of a particular piece (or set) of equipment within a manufacturing enterprise supports the design of the production system. The Equipment Evaluation Tool is based on the MSDD v5.1. It uses the FRs from the MSDD that relate to the design of equipment and identifies which physical characteristics the equipment should have to satisfy these requirements. The Equipment Evaluation Tool allows a qualitative evaluation of the equipment in a gradient of 6 levels of achievement by comparing the physical attributes of the equipment to the descriptions under each one of the levels. The Equipment Evaluation Tool also allows a quantitative evaluation by using the performance metrics for each FR being assessed.

The Equipment Evaluation Tool can be very valuable to a manufacturing enterprise since it serves to measure how well the current design and operation of equipment supports the production system design. The tool can also be very useful in providing a guideline or set of objectives for the improvement of current equipment or the design of new equipment. Another application is to track the progress of a system as the equipment design changes.

Chapter 4: Case Study of Visteon Indianapolis Steering Gear Assembly

This chapter presents the work done in equipment design to support production system design at Visteon Indianapolis. This case study serves as an example of the application of the equipment design framework and the Equipment Evaluation Tool. The project involved concept-level design of equipment for the final assembly of automotive steering gears. The case study centered on the comparison between a high-speed asynchronous line (WIN 88) designed with a traditional mentality of optimizing certain performance metrics, and a proposed assembly cell (U-222) designed to fulfill the FRs from the MSDD relating to equipment design and operation. The comparison was done based on assessments of both systems using the Equipment Evaluation Tool.

The results of the assessment of both the traditional system and the proposed cell using the Equipment Evaluation Tool yielded average achievement levels of 2.26 for the WIN 88 line, and 4.8 for the U-222 cell, out of a maximum of 6. The difference reflects the fact that the U-222 equipment was designed from a systems perspective, to satisfy the

FRs from the MSDD that relate to equipment design, which is precisely what the Evaluation Tool measures. This case study helped to illustrate how the U-222 cell can, when compared to the WIN 88 line, better enable the manufacturing system to achieve the enterprise objectives. In addition, it also highlighted the importance of the Equipment Evaluation Tool as an assessment and design tool, since it focuses on measuring how well the equipment design and operation enables the achievement of the FRs from the MSDD that affect equipment design and operation.

Chapter 1: The Production System Design Framework

A manufacturing firm can only remain competitive in today's business environment if it uses a structured approach for the design of its manufacturing system to ensure that all the different elements of such a system will enable the company to achieve its business objectives. The connection between every aspect of the manufacturing system and how it helps to achieve the business goals must be established. The lack of such a connection can place the manufacturing enterprise at risk of engaging in practices that lead to waste in the form of poor quality and poor ability to trace problems, excessive inventories, long throughput times, poor ergonomics (wasted motions of operators), etc. [Gomez, Dobbs and Cochran, 2000]. Despite the importance of achieving the high-level goals of an organization, all too often production systems are designed without regard to such objectives. An effective approach to establish the connection between the elements of a manufacturing system and the business objectives of an enterprise is the Production System Design framework developed by the Production System Design Laboratory at MIT [Cochran, "Framework" 1999]. This chapter will introduce the work from the PSD Laboratory and its usefulness in the design of manufacturing systems. A manufacturing system designed using the PSD framework will achieve the principles of the Toyota Production System, which are also commonly known as the principles of *lean production*, and therefore those ideas will also be discussed below. Also, the PSD framework uses Axiomatic Design methodology to identify the thought process behind *what* a production system intends to achieve and *how* it intends to achieve it, therefore Axiomatic Design will be briefly introduced below.

Before pursuing any further arguments about the design of systems, it is important to define some terms that will be used throughout this thesis, in particular the difference between the terms *Production System* and *Manufacturing System*. But before that distinction can be made, the term *system* must be understood. A system can be thought of as a set of elements with definite inputs that are acted upon to produce a desired output [Parnaby, 1979]. In the case of production and manufacturing systems the elements that comprise it are: people, equipment, tools, materials, information, etc. The interaction between these elements and sub-systems determines the output of the system, and therefore designers of systems must pay careful attention to ensure that the interactions between the different component elements will produce the desired result [Cochran, "Framework" 1999].

Cochran makes the distinction between manufacturing and production systems as follows:

> 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. The Production System consists of all of the elements and functions that support the manufacturing system [Cochran, "Framework" 1999].

Production System is therefore a broader term than Manufacturing System. A Manufacturing System encompasses all the elements that are directly involved in the process of adding value to the inputs to yield the products of the system. A Production System encompasses a Manufacturing System, together with the supporting elements and resources associated with it. All the resources associated with managing, controlling and measuring the performance of a Manufacturing System are considered to be part of the Production System. Production System Design, therefore, involves not only the design of all the elements of the Manufacturing System (people, equipment, information, etc.) but also the definition of a performance measurement strategy, cost justification of the design and overall design effectiveness.

1.1.- Lean Production – The Toyota Production System

Lean Production is a term coined by the International Motor Vehicle Program (IMVP) and MIT [Womack, Jones and Roos, 1991] to describe a set of methods for designing, operating and managing a manufacturing enterprise that were first used by Toyota, and are therefore also known as the Toyota Production System. This particular manufacturing system design was developed by Toyota between the 1940's and the

1970's to produce high-quality automobiles, respond rapidly and accurately to customer demand and keep their costs at a minimum. Several sources in literature describe the Toyota Production System and have recently attracted attention to lean production practices from manufacturers all over the world [Black, 1991; Monden, 1993; Ohno, 1988; Shingo, 1989; Womack and Jones, 1996; Womack, Jones and Roos, 1991]. Many other names have been associated with the concepts of lean production, or at least with some elements of it, amongst them: Just In Time (JIT), Kaizen, Cellular Manufacturing, World-Class Manufacturing, etc. Many of these terms do not accurately encompass all of the different aspects of lean production and may lead to confusion; therefore in the course of this thesis the author will use *lean production* and *Toyota Production System* to refer to the aforementioned manufacturing system design.

1.1.1.- Development

The Toyota Production System was developed by Toyota Motor Company in Japan starting in the 1940's after the Second World War, and it was a process of continuous change and improvement that was mostly complete by the 1970's but that continues to evolve even today. After WWII, the automobile industry in Japan was very depleted and the market was quite small, with low demand for a high variety of products, therefore Toyota could not compete using the economies of scale (mass production) that automobile manufacturers in the United States were using [Wang, 1999]. Toyota was forced to compete by producing a greater variety of vehicles in smaller numbers, and in the shortest lead-time, while still maintaining low costs and high quality. The result was that Toyota modified its existing production system in a drive to eliminate all the waste, and as a result created a manufacturing system with two fundamental concepts: (1) Just-in-time and (2) autonomation (automation focused on the operators), and a series of other elements and methods that will be described below.

1.1.2.- Principles

The force that brought about the development of the Toyota Production System was the drive to eliminate waste in all its forms from the manufacturing system. TABLE 1 shows the seven types of waste identified by lean production. The elimination of these sources of waste leads to a responsive manufacturing system that can accurately satisfy customer demand in short lead-times, while maintaining high quality, low inventories and minimal costs.

PRODUCTION WASTE	DESCRIPTION
Overproduction	All production that is not demanded from a downstream customer is considered waste. Generally, it is a consequence of production in large batches, and leads to the existence of excessive inventories.
Inventory	All products and materials that are idle somewhere in the manufacturing system – whether they are called inventory or Work In Process (WIP) – are considered waste. Inventories increase the throughput time of the system and also represent capital that is not being productive.
Defective parts	Producing defects constitutes waste since resources (material, operators, equipment, etc.) are used to make parts that will eventually have to be discarded or repaired.
Process waste	Process waste is a result of poor planning of the processing tasks that leads to unnecessary tasks, in the form of excessive processing per se (polishing, grinding, etc.) or excessive clamping into fixtures, reorientations, etc.
Transportation	Moving parts between operations does not add value and is therefore pure waste. Some transportation is always necessary but it should be minimized.
Wasted motion	Excessive motions of the operator to search/reach for tools and parts are considered waste, since it does not properly utilize the operator as a resource to add value to the product.
Idle operators	Operators that are used to oversee the equipment, and simply wait idle for the equipment cycle to complete are not using their time with the maximum efficiency, and the time they spend tied to the equipment and idle is considered waste.

TABLE 1: The Seven Types of Waste in a Manufacturing System

One of the fundamental concepts of the Toyota Production System is the idea of Just-in-time. The concept of Just-in-time is very simple, each production sub-system is to maintain a standard level of inventory, and its downstream customers take what they need from that inventory when they need it. Once product is removed from the inventory, the production sub-system produces only enough products to replenish the standard level of inventory [Ohno, 1988]. That is the idea of a pull system, where each sub-system *pulls* the product they need from previous sub-systems or suppliers, and these upstream processes in turn receive a signal of what to produce based on what is missing from their standard inventory. A refinement on the pull system is the use of cards, or *Kanban* (which is Japanese for card), where cards are used to signal what products and quantities are needed between sub-systems. For a pull system to be effective, the standard levels of inventory must be kept low, and this in turn requires a short throughput time (total time between reception of customer order and delivery of product) for the system. Reducing the throughput time of a system requires simplifying material flow paths (single piece flow); having all the operations in the factory produce at the same cycle time, which is dictated by the pace of customer demand (known as the *takt* time); and leveling the production.

Toyota attempted to balance the production throughout the factory such that all the operations produce at the same pace. The takt time, almost like the heartbeat of the factory, is the rate at which customers demand finished products from the system. One of the innovations of the Toyota Production System was to have each individual process throughout the factory produce at a cycle time lower than the takt time, which was known as Balanced Production. Balanced Production forced the redesign of some processes and equipment, but enabled the simplification of flow paths in the factory since parts could now flow from one process to the next in single-piece succession and still have one part be finished every time the customer demanded one (every takt time that elapsed). Toyota also learned to level the production of different products, such that a wide variety of different vehicles could be made available to the customer with the shortest possible lead-time. Instead of producing in large batches (like the mass production manufacturers were doing), Toyota produced as few parts of each type at one time as possible, and then production switched to a different product, that way making a wide variety of products available in a short period of time. The key conceptual idea that enabled level production was the reduction of setup times, which reduced the time and cost involved in changing over from one product to another, and therefore allowed producing in small run sizes [Shingo, 1989].

The second fundamental concept of the Toyota Production System (together with Just-in-time) is the idea of autonomation, or automation focused on the operators. The new mentality of balanced production led Toyota to design manufacturing sub-systems in which there may be more machines/stations than before, since now each machine can only have a cycle time equal to or less than the takt time. The key conceptual idea that allowed balanced production is that now not every station would be assigned an operator, but instead the operators would now be able to operate multiple machines [Cochran, Course 1999]. In this way the operators' time would be utilized to the fullest, recognizing their place as the most important resource in a factory, as opposed to the mass production mentality of maximizing machine utilization and considering the equipment the most important resource. To allow the operators to work on different machines/stations, each machine must be able to operate independently, stop automatically once its cycle is complete and detect its own errors. This is the idea of autonomation, in which the equipment will typically be manually loaded (since these operations are usually difficult to automate), but it will operate automatically, stop once its cycle is complete and unload automatically. Equipment designed in this way allows operators to simply load a machine, start the cycle and then walk away from it to the next machine to continue to do work, as opposed to being idle waiting for the cycle to complete. Eventually the concept of man-machine separation, together with standard work routines led to cellular manufacturing, which improved the volume flexibility and utilization of workers [Charles, Cochran and Dobbs, 1999].

Lean production rests on the basic principles described above but it also incorporates other common sense ideas. *Kaizen* is one of these elements, and it refers to a concerted effort by everyone in the manufacturing system to continuously improve the system by constantly identifying and eliminating sources of waste. As Wang points out, "Toyota fostered the philosophy of eliminating all root causes of problems so that they never cause another disruption or defect" [Wang, 1999]. 5S was another idea coined by Toyota, which referred to keeping the workplace clean and organized, with "a place for everything and everything in its place." Lean production also introduced changes at levels of the production system outside the pure manufacturing environment. The product design process in lean production attempted to make important decisions early in the process and to emphasize design for manufacturability [Womack, Jones and Roos, 1991]. Supplier relations in lean production attempted to build long-term relations with the suppliers and to work out arrangements advantageous to both parties, as opposed to selecting suppliers from several competitors based on the best offered price [Womack, Jones and Roos, 1991]. Toyota also guaranteed lifetime employment to a good portion of its workforce to improve morale and to allow the work force to participate in the continuous improvement efforts without the fear of losing their job.

1.1.3.- Implementation

As mentioned above, there are many elements that compose what has come to be known as lean production or the Toyota Production System. A thorough understanding of all these elements and their interactions throughout all levels of an organization is needed for a successful implementation of lean production in a particular manufacturing enterprise. Today, many firms have attempted to apply only some of the elements from lean production in isolation from others, without understanding the depth of the interactions between these elements and between the successful implementation of these elements and the achievement of the high-level goals of an organization. Unfortunately, "relatively few firms have been able to reach the level of implementation and refinement that Toyota has demonstrated [precisely] because the relationships between these elements and the design of production systems are not well understood" [Arinez et al., 1999]. The Production System Design Framework introduced below, and in particular the Manufacturing System Design Decomposition provides an effective method to communicate the requirements to incorporate all the different elements of lean production into the design of a manufacturing system. Also, the MSDD illustrates the relationships amongst these elements, and between each one of these elements and how they help to achieve the business goals of the entire company.

1.2.- Axiomatic Design

Axiomatic Design is a fundamental design methodology that structures the process of design to ensure that the end result of the process achieves the initial objectives set for the design. 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].

Axiomatic Design structures the decision-making process for any design into decisions about *what* the design intends to achieve and *how* it intends to achieve it [Suh, 1990]. Design is comprised of three domains, namely the Customer Domain, the Functional Domain and the Physical Domain, and a continuous interaction between these is necessary for the end result of the design process to achieve the initial objectives. FIGURE 1 illustrates the design domains and the interactions between them. The customer domain contains the customer needs, expectations, specifications, constraints, etc. This set of customer requirements leads to the definition of Functional Requirements (FRs), which characterize *what* the design wants to achieve. The FRs, in turn, lead to the identification of Design Parameters (DPs), which contain information about *how* to achieve what is specified in each FR. Each DP is then further decomposed into lower-level FRs, which identify what needs to be done to accomplish that DP. Then a new DP is identified to fulfill each one of these lower-level FRs. This decomposition process continues until all aspects of the design have been thoroughly characterized and the design is therefore complete.

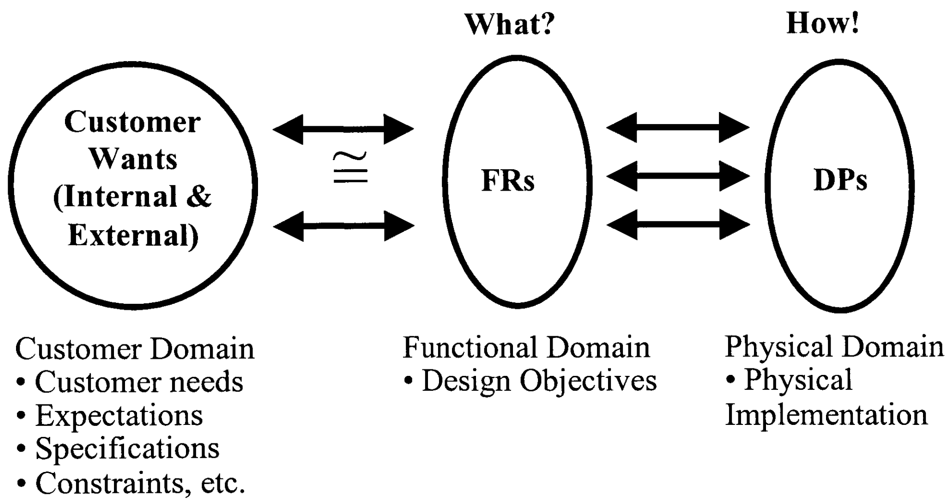


FIGURE 1: The Axiomatic Design Domains [Suh, 1990]

In Axiomatic Design, two axioms govern the development of a good design [Suh, 1990]:

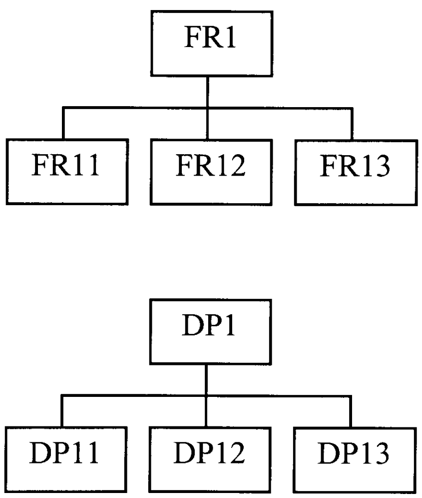
1. *The Independence Axiom:* The first axiom states that an optimal design maintains the independence of the FRs. In this case satisfying a particular FR should not affect the feasibility of satisfying another FR. In the best-case scenario, the DP for an FR can be adjusted without affecting other FRs. If this is not the case, then one or all the FRs infringing on one another should be reformulated to eliminate the interdependency.

2. *The Information Axiom:* The second axiom states that an optimal design should minimize the information content. Therefore the best design is one with no coupling and with a minimum of information content.

It is important to note that the first axiom refers to functional independence and not to physical independence. Several different FRs can affect a single attribute of what is being designed. Physical attributes to achieve different FRs can be combined (physical integration) and still achieve separate FRs (functional independence).

In Axiomatic Design a Design Matrix establishes the relationships of precedence and dependence between the DPs and the FRs. If there is a dependence relationship between a particular FR and a DP then a one (1) or an X will appear in the corresponding place on the Design Matrix. Similarly, if there is no dependence in a particular FR/DP pair then the corresponding place on the Design Matrix will show a zero (0). The completed design matrix shows the state of the design: uncoupled, decoupled or coupled.

The ideal designs are uncoupled, where each DP affects only one FR. These designs are characterized by a diagonal Design Matrix, and the design is path-independent. Decoupled designs are acceptable. In a decoupled (or quasi-coupled) design some DPs affect more than one FR, which makes the Design Matrix triangular, and the design is path-dependent, which means that the order of implementation of the DPs is determined by the relationship between them. Coupled designs are considered poor designs. In a coupled design some DPs affect each other's FRs, which means that the Design Matrix cannot be made triangular. In this case, the adjustment of one DP can prevent the design from satisfying another FR; therefore if a coupled design is to be implemented, it will be highly iterative and unstable. FIGURE 2 illustrates the Design Matrices for these different states defined by Axiomatic Design.



Uncoupled:

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

Decoupled or Quasi-Coupled:

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

Coupled:

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

FIGURE 2: Differences Among Designs Using Axiomatic Design

1.3.- The Production System Design Framework

Production systems have traditionally been designed in isolation from business objectives through a process in which individual subsystems are optimized independent of each other and of the overall system [Cochran, Kim and Kim, 2000]. The resulting systems often are difficult to control and do not meet the enterprise's objectives. The design of manufacturing systems using a comprehensive and coherent methodology has traditionally been practiced only very rarely.

One recent approach to the design of production systems is the Production System Design (PSD) framework [Cochran, 1994; Carrus and Cochran, 1998; Suh, Cochran and Lima, 1998; Cochran, "Framework" 1999]. The PSD framework applies the Axiomatic Design methodology described above to the design of production systems to "clearly define objectives (what we want to do) and the corresponding physical implementation (how it will be done)" [Cochran, "Framework" 1999]. Using Axiomatic Design for the design of production systems leads to designs that are simple, easy to operate and that achieve business objectives. The PSD framework identifies the thought process and the key decisions that need to be made during the design of a production system, and it serves as a method to communicate those decisions to the people in an organization. The PSD framework is useful not only during the design phase of a production system, but also during its deployment and subsequent control. The PSD framework also encapsulates the knowledge from the Toyota Production System literature and experience in such a way that a system designed using the PSD framework will achieve the principles of lean production.

The key advantage of the Production System Design framework is that it provides the connection between the high-level goals of an organization and the many decisions that must be made to design the subsystems that are part of the whole (equipment, control system, material replenishment, etc.) Having this clear and well-defined connection between the subsystems and the high-level goals enables the entire system to achieve these enterprise objectives, which is ultimately the driving force of any manufacturing company.

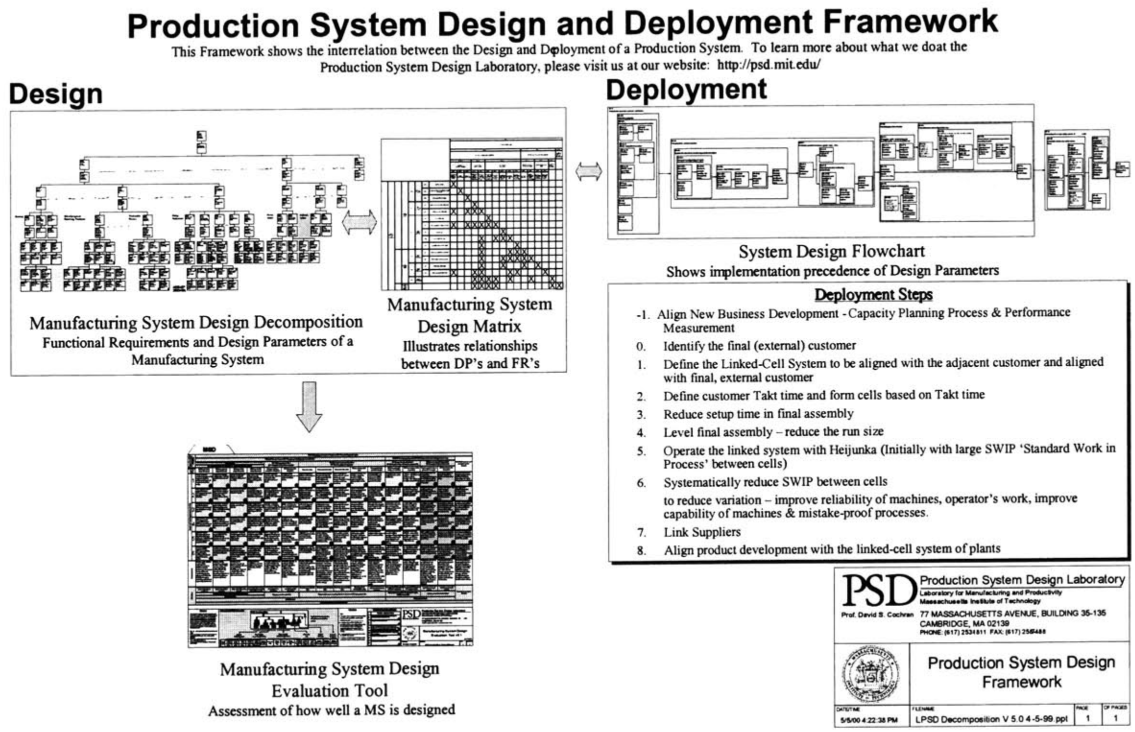


FIGURE 3: The Production System Design and Deployment Framework

FIGURE 3 shows the PSD framework with all of its elements, namely:

- The Manufacturing System Design Decomposition.
- The Manufacturing System Design Matrix.
- The Manufacturing System Design Evaluation Tool, and
- The Production System Design and Deployment Flowchart and Steps for Implementation.

The MSD Decomposition and the MSD Evaluation Tool will be highlighted in the following sections due to their relevance to the purpose and scope of this thesis. For further information on the remaining elements of the PSD framework please refer to the literature associated with the PSD framework [Cochran, 1994; Carrus and Cochran, 1998; Suh, Cochran and Lima, 1998; Cochran, "Framework" 1999]. Also, several examples of the application of the PSD framework to the design of particular production systems can be found in the literature [Arinez et al., 1999; Bröte et al., 1999; Charles, Cochran and Dobbs, 1999; Duda et al., 1999].

1.3.1.- The Manufacturing System Design Decomposition

The Manufacturing System Design Decomposition (MSDD) is the centerpiece of the Production System Design framework. The MSDD "identifies the design relationships to achieve a 'lean' production system design" [Cochran, "Framework" 1999]. The MSDD uses Axiomatic Design methodology 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 MSDD identifies first the highest-level goal of an organization, *FR1: Maximize long-term return on investment (ROI)*. The process of Axiomatic Design now calls for the identification of a Design Parameter to satisfy FR1, which is *DP1: Manufacturing System Design*. Since the DP does not provide enough detail to implement the design, further decomposition is needed and lower-level FRs are developed to satisfy FR1. The process continues with the identification of DPs for these lower-level FRs, and then more FRs are identified where needed. The high-level FRs and DPs are decomposed into lower-level pairs of FRs and DPs that relate to various aspects of the manufacturing system. Following this process repeatedly and comprehensively produces a series of FRs and DPs that identifies the thought process behind the design of each and every subsystem within the manufacturing enterprise. In general, the MSDD identifies not only the *how* that Toyota implemented but also the *why* of manufacturing system design [Cochran, "Framework" 1999]. The key importance of the MSDD is not only that it establishes the FRs and DPs for the design of each and every subsystem, but also that it clearly depicts the link between each one of those FRs and DPs with the high-level objectives of the enterprise [Gomez, Dobbs and Cochran, 2000].

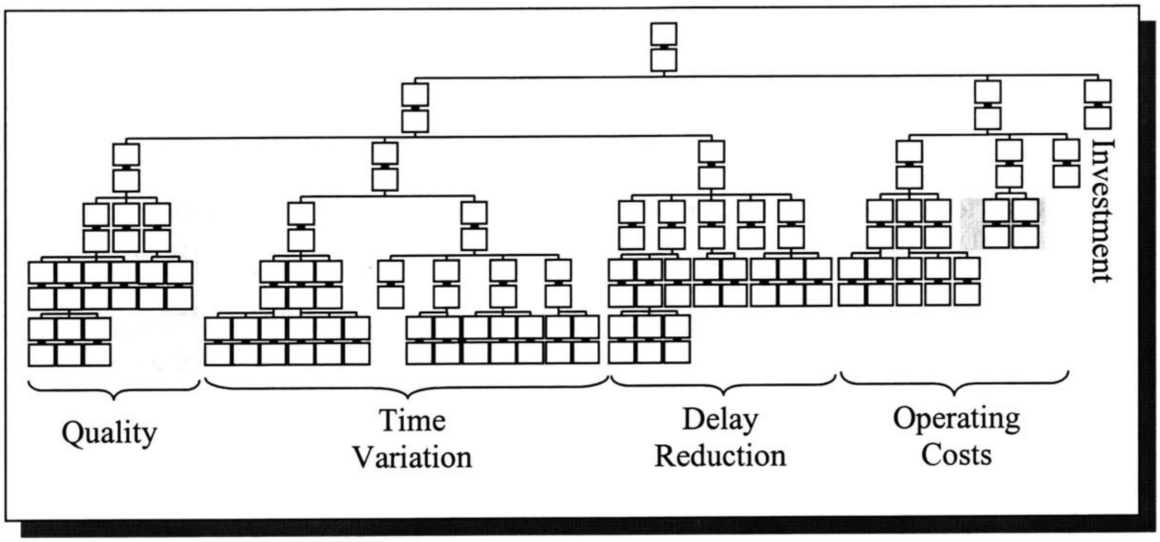


FIGURE 4: Schematic View of the Manufacturing System Design Decomposition v5.1

The Manufacturing System Design Decomposition has evolved through several different versions [Cochran, 1994; Suh, Cochran and Lima, 1998; Cochran, "Framework" 1999] and it continues to be a living document. The latest version of the MSDD, version 5.1 was developed at the Production System Design Laboratory at the Massachusetts Institute of Technology with the participation of: David Cochran, Jorge Arinez, Staffan Bröte, Brandon Carrus, Jose Castañeda-Vega, Alex Chu, Micah Collins, Daniel Dobbs, James Duda, David Estrada, Deny Gomez, Jongyoon Kim, Yong-Suk Kim, Kristina Kuest, Jochen Linck, Ania Mierzejewska and Andrew Wang [Production System Design Laboratory, 2000]. FIGURE 4 shows a schematic view of the MSDD v5.1, with indications of which section of the decomposition refers to which element of the manufacturing system. The complete MSDD v5.1 is included in Appendix A, starting on page 101.

An important change in v5.1 of the MSDD is the incorporation of Performance Metrics (PMs) for each Functional Requirement identified in the decomposition. The PM associated with each FR allows a quantitative evaluation of whether that particular FR has been achieved and to which level. The highest-level performance metric is *PM1: Return on investment (ROI) over production system lifecycle*, which is associated with *FR1: Maximize long-term return on investment.* Similarly, each of the lower-level FRs is associated with a performance metric, which the designer of the production system can use to evaluate how well each particular FR is achieved. Appendix A shows the PMs for all the FRs in the MSDD v5.1. It is worthwhile to mention that no target values or acceptable ranges have been set for any of the performance metrics indicated in the MSDD due to the differences encountered across different industries or even across different companies for the same metrics. It is up to the designer using the MSDD to set the targets and acceptable ranges for the PMs provided, in the context of the particular industry and the application where the MSDD is being used.

1.3.2.- The Manufacturing System Design Evaluation Tool

The Manufacturing System Design Evaluation Tool is derived from the MSDD. It evaluates to what degree a particular manufacturing enterprise has achieved the FRs from the MSDD. In particular the MSD Evaluation Tool assesses FRs that are mostly in the fourth level of the decomposition. The MSD Evaluation Tool has been developed to assess the design of a manufacturing system, which contrasts with traditional ways of measuring systems based on their performance, with metrics such as unit labor cost and machine utilization [Chu and Cochran, 2000]. Each FR is evaluated in a gradient of six levels of achievement, which correspond to the following general system characteristics: (1) Job Shop or Departmental Layout; (2) Departments Arranged by Product Flow; (3) Assembly Line or Transfer Line; (4) Pseudo-Cell; (5) Assembly or Machining Cells, and (6) Linked-Cell Manufacturing System.

The MSD Evaluation Tool "provides a mechanism to measure the implementation adequacy of new system designs based on the system design represented by the [MSDD]" [Cochran, "Framework" 1999]. It provides a method to evaluate different elements of the manufacturing system and to identify which areas are in most need of improvement. Since the MSD Evaluation Tool provides descriptions of what the ideal characteristics of the system should be to score in the highest level, it also serves as a design tool and helps to provide designers with direction during the design stage of the manufacturing system so that it properly achieves the FRs from the MSDD. In short, the MSD Evaluation Tool allows the user to know where the system is, and where it should be, all in one sheet of paper [Cochran, "Framework" 1999]. FIGURE 5 shows the latest version of the MSD Evaluation Tool, developed by David Cochran, Andrew Wang and Alex Chu from the Production System Design Laboratory at the Massachusetts Institute of Technology.

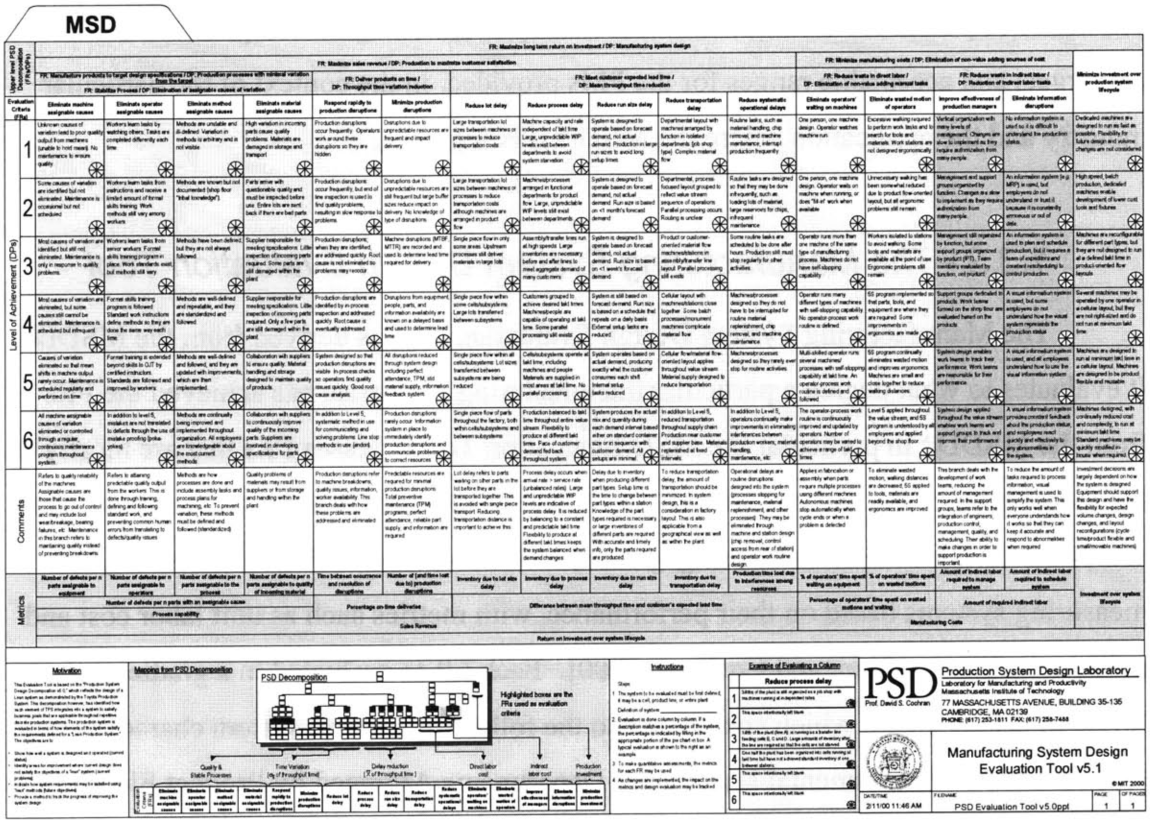


FIGURE 5: Manufacturing System Design Evaluation Tool v5.0 [Chu and Cochran, 2000]

The MSD Evaluation Tool is highlighted in this chapter due to the relevance to the rest of the thesis. Chapter 3 introduces the Equipment Evaluation Tool, which bears many similarities with the MSD Evaluation Tool. The format is noticeably similar, but also the structure, the levels of achievement and the overall usage of both evaluation tools is purposely similar. The Equipment Evaluation Tool, of course, focuses on assessing only an element of the manufacturing system, the equipment, while the MSD Evaluation Tool provides a general assessment.

1.4.- Equipment Design and the Production System Design Framework

As mentioned above, the Production System Design framework identifies the thought process and decisions that must be made to design a manufacturing system that captures the principles of the Toyota Production System. The PSD framework encapsulates knowledge and experience from lean production about the design and operation of all the different elements of a manufacturing system. A subset of the Functional Requirements identified in the MSDD relate to the design and operation of equipment. Chapter 2 will focus on identifying this subset of FRs that relate to equipment design and operation. This set of FRs serves as a framework that allows the designer to design equipment that will enable the production system to achieve its high-level objectives.

Chapter 3 introduces the Equipment Evaluation Tool, which assesses how well the physical characteristics of a particular piece or set of equipment achieve the FRs from the MSDD that relate to the equipment. The Equipment Evaluation Tool could be considered an addition to the Production System Design framework that focuses on assessing the current state of the equipment (in terms of achieving the FRs from the MSDD) and setting goals for the design and improvement of equipment. In a similar fashion, further additions to the PSD framework could be developed that focused on other elements of the production system, like the information system, the control strategies, the operators, etc.

1.5.- Summary

This chapter introduced the Production System Design (PSD) framework developed by the Production System Design Laboratory at the Massachusetts Institute of Technology. The chapter explained the concepts of the Toyota Production System, also known as lean production. The Toyota Production System is a set of methods for designing, operating and controlling a production system that have the ultimate objective of eliminating waste in all its forms from the system. Lean production follows two fundamental principles: Just-In-Time and autonomation (or man-machine separation), which together with a set of common sense tools and ideas leads to a responsive manufacturing system that can accurately satisfy customer demand in short lead-times, while maintaining high quality, low inventories and minimal costs. The chapter also introduced Axiomatic Design, a methodology that provides a scientific base for design. Axiomatic Design is a process of making decisions about *what* a design intends to achieve (Functional Requirements) and *how* it intends to achieve it (Design Parameters). An ideal design under Axiomatic Design is one that follows the two central axioms: (1) the independence of the Functional Requirements, and (2) a minimal information content.

The PSD framework applies Axiomatic Design methodology to the design of a production system to define its objectives (the what's) and the corresponding physical implementations (the how's). Using Axiomatic Design for the design of production systems leads to designs that are simple, easy to operate and that achieve business objectives. The PSD framework identifies the thought process and the key decisions that need to be made during the design of a production system, and it serves as a method to communicate those decisions to the people in an organization. The PSD framework encapsulates the knowledge from the Toyota Production System literature and experience in such a way that a system designed using the PSD framework will achieve the principles of lean production.

Chapter 2: Equipment Design and the Production System Design Framework

The Production System Design framework introduced in Chapter 1 identifies the thought process and decisions that must be made to design a manufacturing system that captures the principles of the Toyota Production System. The PSD framework encapsulates knowledge and experience from lean production about the design and operation of all the different elements of a manufacturing system. The PSD framework incorporates system-level requirements in a variety of different areas related to the production system ranging from production investment to producing high quality products. In addition to its use as a general design tool for systems, the PSD framework also serves to communicate system requirements to the designers of subsystems [Arinez et al., 1999]. In particular, the Functional Requirements identified in the MSDD communicate system requirements to the many different elements of the manufacturing system, including the equipment, the information system, the material handling system, the operators, etc. Of particular interest in the scope of this thesis is the design and operation of equipment; therefore this chapter will study the relation between manufacturing system design requirements and equipment design.

It is important to make the distinction between the terms *machine* and *equipment*, since these terms are many times used interchangeably which might lead to confusion. According to the Merriam-Webster Dictionary, the term *machine* refers to the mechanical behavior and interaction of the components of the device used to accomplish a specific purpose, while the term *equipment* is broader and refers to all the implements (machines, tools, etc.) that are used to complete an operation or activity. In the work by Arinez and Cochran [Arinez, 2000; Arinez and Cochran, 1999] the term *equipment* is used because of its more general nature and its direct reference to the completion of an operation. This work will give preference to the term *equipment* as well, for the same reasons.

Since manufacturing firms typically have many different types of equipment (automated machines, manual tools, etc.) as part of the production system, it is important to have a structured process by which system requirements can be communicated to all these different types of equipment [Arinez, 2000]. This chapter will present a summary of the equipment design framework developed by Arinez and Cochran to design equipment that meets the requirements of the production system identified by the PSD framework, for further details refer to the associated literature [Arinez, 2000; Arinez and Cochran, 1999; Arinez et al., 1999].

Arinez and Cochran introduce a twofold framework for the design and operation of equipment to satisfy the requirements identified by the PSD framework [Arinez and Cochran, 1999]. The same framework for the design and operation of equipment will be used in this thesis – with due credit awarded to its original authors – except that it will be updated to reflect the latest changes and latest version of the PSD framework. First, the approach involves the identification of the Functional Requirements from the MSDD that relate to the design and operation of equipment. This set of FRs that affect the equipment allows the generation of guidelines that must be followed by the equipment designers to satisfy the system requirements from the PSD framework. Secondly, the approach involves the extension of Axiomatic Design to equipment design to more closely link it with the design of the overall system using the PSD framework [Arinez and Cochran, 1999].

Each one of the two approaches described above as part of the equipment design framework is more suitable to be used in a particular equipment design environment. Arinez and Cochran make the distinction between manufacturing environments in which the design of equipment involves a high degree of customization and concurrency [Arinez and Cochran, 1999]. Customization refers to how unique the equipment is when compared to other readily available equipment. Concurrency refers to the extent to which the customer (the manufacturing enterprise) and the equipment builder (internal or external) communicate and interact during the design process. FIGURE 6 shows the four possible equipment design environments in terms of customization and concurrency and the characteristics of each.

		Customization	
		Low	High
Concurrency	Low	*Quadrant 1:* Standard equipment. Requirements developed by equipment builder to meet a wide variety of customer applications and based on market data and experience.	*Quadrant 2:* Custom equipment. Requirements developed by customer and provided to the equipment builder. Customer has knowledge and capability to write requirements.
	High	*Quadrant 3:* Standard equipment. Customer has its own set of requirements, however, customer and equipment builder work together to configure standard equipment.	*Quadrant 4:* Custom equipment. Requirements developed jointly by customer and builder. Both parties participate in detailed design of equipment.

FIGURE 6: Different Levels of Customization and Concurrency in Equipment Design [Arinez, 2000]

With the different scenarios in terms of levels of customization and concurrency in mind, the first method that was described – the generation of guidelines from the PSD framework – is more suitable for equipment design with relatively low levels of concurrency and customization (Quadrant 1), although it is also applicable for the environments of quadrants 2 and 3. In general, the process of designing equipment with a low level of customization and concurrency involves the communication of a set of requirements from the customer to the equipment builder; requirements about the processes, configuration of equipment, safety, purchasing, etc. Therefore, the development of another set of requirements to satisfy the system requirements of the enterprise from the PSD framework is well suited to guide the design of equipment in this environment. This set of guidelines based on the PSD framework would complement the other guidelines provided to the equipment builder and guide the design process so that the equipment achieves the system requirements.

The second method – the application of Axiomatic Design to the design and operation of equipment – is better suited for equipment design with a high degree of customization and concurrency (Quadrant 4). When highly customized equipment is required, along with the corresponding need for a concurrent design effort, Axiomatic Design can provide a common methodology to be followed by both the customer and the equipment builder during the design process for the equipment. By designing the equipment using Axiomatic Design, both the customer and the equipment builder can participate in the specification of the relevant FRs and DPs to completely specify the equipment. Using this methodology allows both parties to participate and have a say in the specification of each FR/DP pair, and therefore the equipment should satisfy the requirements specified by the customer, especially in terms of achieving the system requirements from the PSD framework.

2.1.- Generation of Equipment Design Guidelines from the PSD framework

The first approach identified by Arinez and Cochran for the design of equipment to satisfy the system requirements from the PSD framework is to generate a set of guidelines to be provided to equipment designers when designing equipment. As mentioned above, this approach is more suitable for manufacturing environments where equipment is designed with a relatively low degree of concurrency and customization. To some extent "this approach regards the design of equipment as a 'black-box' activity to which requirements must be supplied" [Arinez and Cochran, 1999]. Such an approach is well suited for companies that provide their equipment vendors with a set of requirements about the processes, configuration of equipment, safety, purchasing, etc. and ask the vendor to complete the detailed design of the equipment. Therefore, the development of a set of guidelines that conveys the system requirements placed on the equipment by the PSD framework is an appropriate method to guide the design of equipment in this environment.

The first step in this approach is the identification of the system requirements from the PSD framework that relate to the design and operation of equipment. As mentioned above, a subset of the Functional Requirements identified in the MSDD relate to the design and operation of equipment. In identifying those FR/DP pairs from the MSDD, the critical question that must be answered is "Does this particular FR/DP pair affect the design and operation of equipment?" Following this methodology, the subset of FR/DP pairs from v5.1 of the MSDD that affect equipment design and operation has been identified. FIGURE 7 shows a schematic representation of where the FR/DP pairs that affect equipment design and operation appear on the MSDD v5.1, and TABLE 2 lists the FR/DP pairs and a comment explaining how each FR/DP pair affects the design and operation of the equipment. Notice that there are many FR/DP pairs that can potentially influence the design and operation of equipment (22 pairs in total) and that they appear at all levels of the decomposition and throughout all its different branches. This fact only reinforces the importance of the equipment as a critical element of the manufacturing system. It also serves to make the point that careful attention must be paid to the design of equipment, otherwise the manufacturing enterprise runs the risk of being unable to meet many of its system requirements and therefore being unable to achieve its high-level objectives.

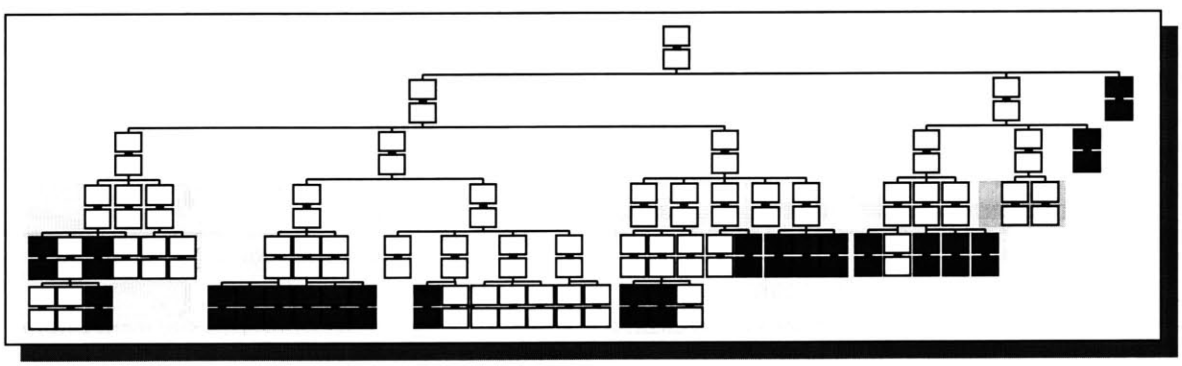


FIGURE 7: FR/DP Pairs from the MSDD v5.1 that Affect Equipment Design and Operation

FUNCTIONAL REQUIREMENT	DESIGN PARAMETER
FR-Q11 Eliminate machine assignable causes (of variation)	DP-Q11 Failure mode and effects analysis
COMMENT: Equipment design should strive to maintain the quality of the output (as opposed to only preventing breakdowns) and to manufacture products to target design specifications and with minimal variation from the mean every cycle	
FR-Q13 Eliminate method assignable causes (of variation)	DP-Q13 Process plan design
COMMENT: The impact of the order and type of operations selected to manufacture a product on the ability to achieve system requirements must be considered	

FUNCTIONAL REQUIREMENT	DESIGN PARAMETER
FR-Q123 Ensure that operator human errors do not translate to defects	DP-Q123 Mistake proof operations (Poka-Yoke)
COMMENT: The equipment should prevent the operator from making any error that would lead to a defective part	
FR-R111 Identify disruptions when they occur	DP-R111 Increased operator sampling rate of equipment status
COMMENT: The equipment should allow the operator to identify production disruptions immediately when they occur	
FR-R112 Identify disruptions where they occur	DP-R112 Simplified material flow paths
COMMENT: The equipment should allow the operator to identify the location of production disruptions when they occur	
FR-R113 Identify what the disruption is	DP-R113 Context sensitive feedback
COMMENT: The equipment should allow the operator to identify the nature of production disruptions when they occur	
FR-R121 Identify correct support resources	DP-R121 Specified support resources for each failure mode
COMMENT: The equipment should enable the operator to identify the correct support resource needed to resolve a disruption when one occurs	
FR-R122 Minimize delay in contacting correct support resources	DP-R122 Rapid support contact procedure
COMMENT: The equipment should enable the operator to immediately contact the correct support resource needed to resolve a disruption when one occurs	
FR-R123 Minimize time for support resource to understand disruption	DP-R123 System that conveys what the disruption is
COMMENT: The equipment should enable the support resource to immediately understand the problem when one occurs, so that it can be immediately resolved	
FR-P121 Ensure that equipment is easily serviceable	DP-P121 Machines designed for serviceability
COMMENT: Equipment should be designed to allow simple and rapid service operations.	
FR-T221 Ensure that automatic cycle time is less than or equal to the minimum takt time	DP-T221 Design of appropriate automatic work content at each station
COMMENT: Equipment should be designed such that all automatic tasks are completed in a time less than or equal to the minimum takt time	
FR-T222 Ensure that manual cycle time is less than or equal to the minimum takt time	DP-T222 Design of appropriate operator work content / loops
COMMENT: Equipment should be designed such that the operator can complete all the manual tasks at a station in a time less than or equal to the minimum takt time	

FUNCTIONAL REQUIREMENT	DESIGN PARAMETER
FR-T32 Produce in sufficiently small run sizes	DP-T32 Design quick changeover for material handling and equipment
COMMENT: Equipment should be designed to changeover quickly between different products to enable production in small run sizes	
FR-T51 Ensure that support resources don't interfere with production resources	DP-T51 Subsystems and equipment configured to separate support and production access requirements
COMMENT: Equipment should allow access for routine service operations (lubrication, chip removal, coolant flush, etc.) from the rear of the station to prevent disrupting production activities	
FR-T52 Ensure that production resources (people / automation) don't interfere with one another	DP-T52 Ensure coordination and separation of production work patterns
COMMENT: Equipment should be designed to ensure that different production operators have separate access points	
FR-T53 Ensure that support resources (people / automation) don't interfere with one another	DP-T53 Ensure coordination and separation of support work patterns
COMMENT: Equipment should be designed to ensure that different service workers have separate access points	
FR-D11 Reduce time operators spend on non-value added tasks at each station	DP-D11 Machines and stations designed to run autonomously
COMMENT: Equipment should be designed to prevent tying the operator to the station waiting for an automatic cycle to be completed	
FR-D21 Minimize wasted motion of operators between stations	DP-D21 Machines / stations configured to reduce walking distance
COMMENT: The width and spacing of the equipment should be kept to a minimum to reduce operator's walking distance	
FR-D22 Minimize wasted motion in operators' work preparation	DP-D22 Standard tools / equipment located at each station (5S)
COMMENT: Equipment should be designed such that the operator spends minimal time preparing the work (positioning, placing into a fixture, etc.)	
FR-D23 Minimize wasted motion in operators' work tasks	DP-D23 Ergonomic interface between the worker, machine and fixture
COMMENT: Equipment should be designed such that fixtures, tools and materials are located to minimize wasted operator motions	
FR123 Minimize facilities cost	DP123 Reduction of consumed floor space
COMMENT: Equipment should be designed with the smallest possible footprint to minimize overhead cost. It should not require special facilities (special power, controlled temperature, clean room, large chip removal systems, etc.) whenever possible	

FUNCTIONAL REQUIREMENT	DESIGN PARAMETER
FR13 Minimize investment over production system lifecycle	DP13 Investment based on a long-term strategy
COMMENT: Equipment should support the system design and have the flexibility for expected volume changes, design changes and layout reconfiguration changes (cycle time; product flexibility and small/movable machines)	

TABLE 2: FR/DP pairs from the MSDD v5.1 that Affect Equipment Design and Operation

The next step that is necessary as part of this approach is the compilation of a set of guidelines that can be given to the equipment designer to ensure that the final design of the equipment will satisfy the system requirements. The guidelines are based on the information on TABLE 2, the FR/DP pairs that affect equipment design. However, the guidelines will be specific to each piece or set of equipment being designed, and as such might filter or transform this global set of requirements (from the MSDD) into a more specific set of requirements that more accurately corresponds to the particular type of equipment being designed [Arinez, 2000]. For example, if the equipment being designed requires that a part be loaded onto it with a feature facing up to correctly complete the operation, then *FR-Q123 Ensure that operator human errors do not translate to defects* should be made specific as in: "Ensure that equipment forces operator to load part with feature facing up". Also, the guidelines that are developed should include additional information on how to achieve the specific FR/DP pairs for the equipment in question. In particular, the guidelines should specify the exact mechanical, electrical and other relevant properties that the equipment must have (or the appropriate ranges of properties that are acceptable) to achieve the FR/DP pairs identified in TABLE 2. For example, for *FR-D21 Minimize wasted motion of operators between stations*, and its associated *DP-D21 Machines / stations configured to reduce walking distance*, the guidelines should specify: "the stations and/or machines must have a maximum width of X feet." The exact values that are chosen for the particular mechanical, electrical or other relevant properties depend on the individual circumstances of the equipment being designed. But in short, the guidelines – together with a set of requirements about the processes, safety, purchasing, etc. – should provide enough direction to complete the detailed design of the equipment.

2.2.- Application of Axiomatic Design to the Design of Equipment

The second approach identified by Arinez and Cochran for the design of equipment to satisfy the system requirements from the PSD framework is to apply Axiomatic Design directly to the design of equipment. As mentioned above this approach is more suitable for manufacturing environments where highly customized equipment is used, which requires a high degree of concurrency during the design process (Quadrant 4 in FIGURE 6, on page 37). When highly specialized equipment is required, along with the corresponding need for a concurrent design effort, Axiomatic Design can provide a common methodology to be followed by both the customer and the equipment builder during the design process for the equipment. Using Axiomatic Design for the design of the equipment allows the equipment designer to produce designs that better integrate the system requirements identified by the PSD framework, which have also been generated using Axiomatic Design [Arinez and Cochran, 1999].

This methodology involves the development of an Equipment Design Decomposition for the design of the equipment in question using Axiomatic Design. The process of Axiomatic Design of the equipment begins with the identification of the high-level requirement that the equipment must fulfill, then the identification of a physical implementation to fulfill that requirement, and then further decomposition into lower-level FRs and DPs, as described in section 1.2. This decomposition process for equipment is illustrated using an example from Arinez and Cochran for the design of a CNC milling machine [Arinez and Cochran, 1999]. The high-level functional requirement for this machine is to mill a feature for a given part geometry, which represents the need that led to the design of the milling machine. FIGURE 8 shows the top two levels of the Equipment Design Decomposition for the design of the CNC mill.

FR1 Mill part feature geometry	**FR11** Move tool relative to part	**FR1** CNC milling machine	**DP12** Drive system
	FR12 Provide physical support for subsystems		**DP12** Machine structure
	FR13 Remove material		**DP13** Cutting tool
	FR14 Hold part		**DP14** Work-holding system
	FR15 Hold cutting tool		**DP15** Tooling system
	FR16 Remove chips from machine		**DP16** Chip removal system
Functional Domain		**Physical Domain**	

FIGURE 8: Top Levels of an Axiomatic Design Decomposition for a CNC Milling Machine [Arinez and Cochran, 1999]

Axiomatic Design methodology states that DPs at a particular level are decomposed into lower-level FRs to identify all the requirements that are necessary to achieve that DP. This process must be continued until the decomposition completely describes the entity being designed. This same process is followed in the design of equipment, except that in this case the requirements from the MSDD play a key role in the development of sub-FRs for the Equipment Design Decomposition (EDD). The decomposition process for the design of equipment must achieve the system requirements placed on the equipment. In particular, the subset of requirements from the MSDD that affect equipment design and operation (refer to TABLE 2) provide a guideline for the decomposition process for the equipment. This set of FRs contains the requirements that the equipment must meet in order to achieve the system goals and as such it serves as a guide to design the equipment such that it supports the production system design.

Each FR/DP pair from TABLE 2 identifies a particular requirement that the equipment must achieve, and as such it must be acknowledged during the decomposition process that leads to the EDD. The process of generating sub-FRs in the EDD to completely describe all the physical elements of the equipment is linked to the MSDD in the sense that these physical elements of the equipment must achieve the FRs stated in the MSDD that affect the equipment. FIGURE 9 shows a schematic view of the link between the MSDD and the EDD. In that example, the decomposition of the FR/DP pair on the EDD that describes the fixture that holds the part is affected by several system requirements from the MSDD. These system FRs ensure that the fixture prevents the operator from loading the part incorrectly, can be easily loaded with different parts, and can be loaded quickly to reduce the time the operator spends using it. The FR/DP pairs from TABLE 2 therefore provide a view of the high-level requirements on the equipment that guides the generation of the sub-FRs for the EDD [Arinez and Cochran, 1999].

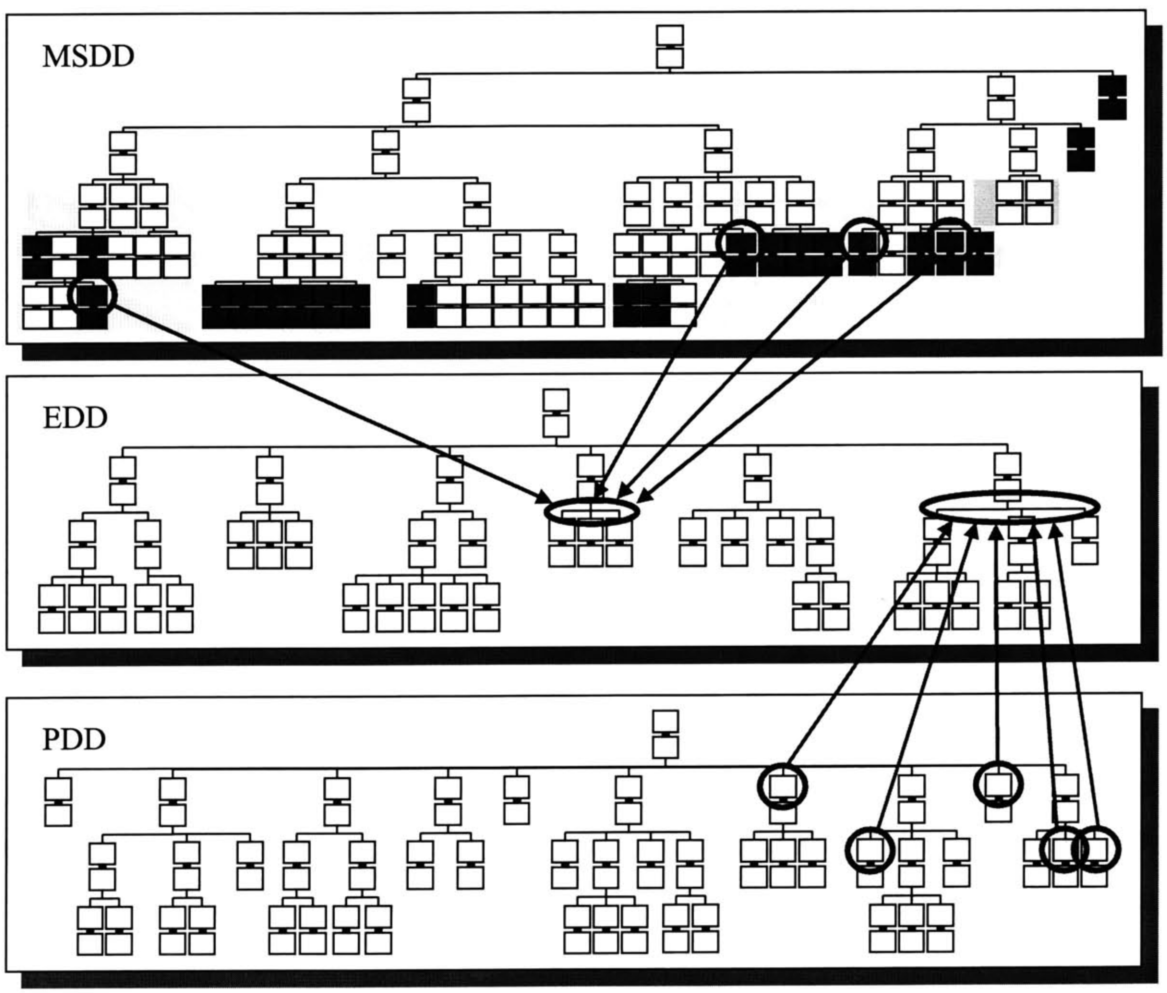


FIGURE 9: Schematic View of Links Between the MSDD, the EDD and the PDD

The system requirements from the MSDD are, of course, in addition to the requirements that the design of the product places on the equipment, influencing the design of its particular elements. When product design also follows the Axiomatic Design methodology, then a link can also be established between the Product Design Decomposition (PDD) and the EDD. In this case the product design requirements (FRs) and physical implementation (DPs) will directly affect the generation of sub-FRs in the EDD. FIGURE 9 also shows a schematic view of the link between the EDD and the PDD. In this case, several FRs from the PDD influence the decomposition of an FR that describes a particular subsystem of the equipment. In short, the method of applying Axiomatic Design for the design of highly customized equipment leads to the generation of an Equipment Design Decomposition, which is closely linked to the MSDD and to the Product Design Decomposition (See FIGURE 9). The link between the EDD and the MSDD and the PDD is in the sense that both of the latter identify a set of requirements that guide the decomposition process of the former.

2.3.- Summary

This chapter presented a summary of the equipment design framework developed by Arinez and Cochran to design equipment that meets the requirements of the production system identified by the PSD framework [Arinez, 2000; Arinez and Cochran, 1999; Arinez et al., 1999]. Chapter 1 presented how the PSD framework identifies the key decisions and the thought process that must be followed to design a manufacturing system that cascades its high-level objectives to low-level requirements specific to equipment design and implementation. The MSDD communicates the system requirements to the designers of subsystems, and of particular interest in the scope of this thesis are the requirements placed on the design of equipment. A subset of the FRs and DPs identified by the MSDD affect the design of equipment, and that subset serves as the basis for a framework for the design of equipment that achieves the requirements of the manufacturing system.

A twofold framework was presented, following the structure of the work by Arinez and Cochran. The first method consists in the identification of the subset of FRs/DPs from the MSDD that affect equipment design, and the further use of those requirements to elaborate guidelines to be supplied to the equipment designers. These guidelines build on the requirements from the MSDD and include specific information on the mechanical, electrical and other relevant physical properties that the equipment must have to achieve the system requirements. The second method involves the direct application of Axiomatic Design methodology to the design of equipment by developing an Equipment Design Decomposition (EDD). In this method, a link is established between the EDD and the MSDD in which the process of decomposition of the EDD is guided by the system requirements from the MSDD. The FR/DP pairs from the MSDD that affect equipment design guide the decomposition of particular FRs in the EDD to ensure that the specifications for individual components of the equipment satisfy the system requirements. This link ensures that the EDD provides a detailed description of the physical properties of the equipment to achieve the system requirements from the MSDD.

Chapter 3: Equipment Evaluation Tool

This chapter presents an Equipment Evaluation Tool that can be used to assess how well the physical characteristics of a particular piece or set of equipment satisfy the functional requirements placed on it during the production system design phase. Chapter 1 outlined the importance of designing a production system with the high-level enterprise objectives in mind and also presented a framework for the design of production systems. The Equipment Evaluation Tool presented here complements the Production System Design Framework presented above (see FIGURE 3 on page 28) since it aids in the design and operation of the equipment, which is in turn a critical aspect of any manufacturing venture. FIGURE 10 shows the modified PSD Framework that includes the Equipment Evaluation Tool and emphasizes the contribution of this work to the research being carried out at the Production System Design Laboratory at MIT.

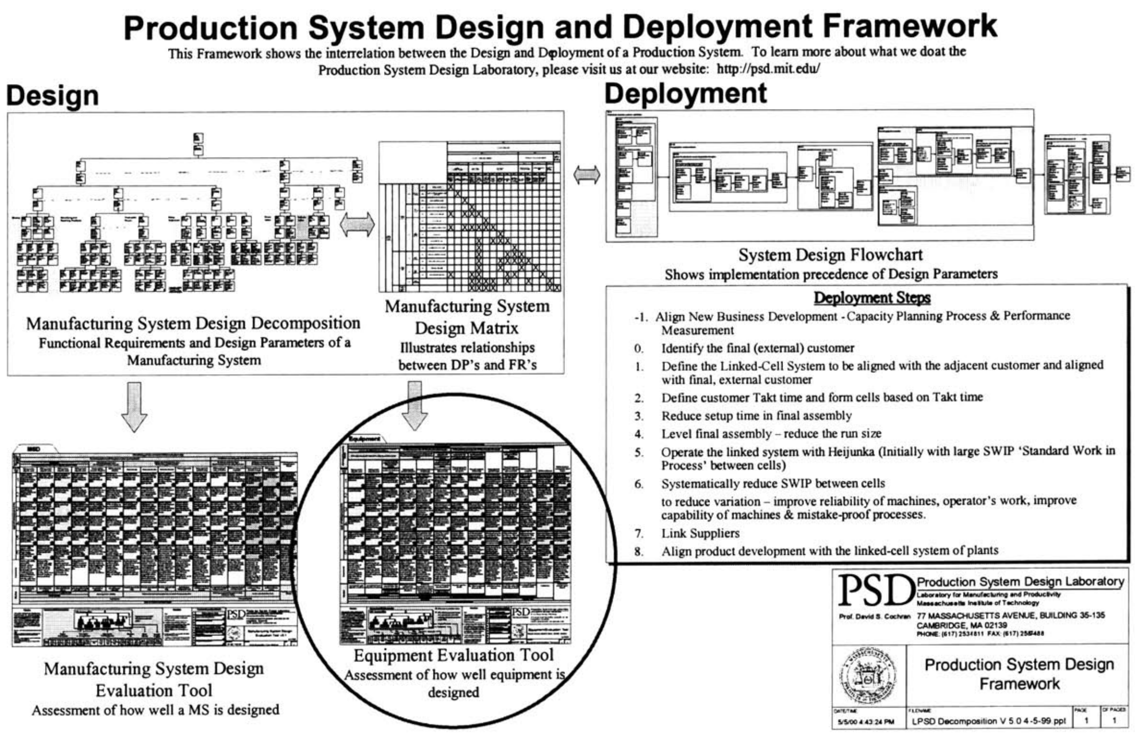


FIGURE 10: Modified PSD Framework Showing the Equipment Evaluation Tool

The Equipment Evaluation Tool is intended to be a document with practical use in the design and operation of equipment, since it can assess how well the equipment meets the functional requirements placed on it during the overall system design phase. As a design tool, this document can also be used to ensure that equipment designs better align with overall manufacturing system objectives. It can also be used to identify problems with existing equipment and to set goals for this equipment to be improved to better satisfy the functional requirements placed on it by the Manufacturing System Design Decomposition (MSDD). The author would like to acknowledge the collaboration from Daniel C. Dobbs and Prof. David S. Cochran in the development of the Equipment Evaluation Tool [Gomez, Dobbs and Cochran, 2000], whose input was very valuable to complete this work.

3.1.- Motivation

One of the important topics covered in Prof. David Cochran's dissertation [Cochran, 1994] and his teachings in Production System Design [Cochran, Course 1999], is that systems evolve based on how they are measured. An example of how this is the case is the traditional focus of manufacturing enterprises on maximizing equipment utilization. To ensure that equipment is used to its full capability, operators monitor the machines constantly, and this monitoring frequently translates into the operator wasting much time waiting for a machine to complete its cycle [Cochran, Kim and Kim, 2000]. Since one operator is tied to one machine/station, then the traditional mentality is that to reduce direct labor costs, the equipment must be designed to maximize the number of cycles an operator can complete in a certain period of time. This drive to reduce labor costs results in increasing the speed of the machine. This scenario, all too common in today's manufacturing industry, sacrifices throughput time, inventories and the ability to trace and resolve quality problems. It is also a good example of how the design of equipment evolves based on how manufacturing is measured, in this case, machine utilization and direct labor costs.

The Equipment Evaluation Tool presented here provides a tool to aid in the design and operation of equipment from a manufacturing system design perspective, as opposed to the perspective of particular measures that often lead the equipment design astray. Since the equipment is such an integral part of any manufacturing enterprise and it can determine the way that a system is both operated and measured, it is important to ensure that the equipment will enable the system to achieve enterprise-wide goals. As mentioned in previous chapters, the MSDD identifies a series of Functional Requirements (FRs) for the design of a manufacturing system, and a subset of these requirements influences the design and operation of equipment. To ensure that the equipment conforms to the FRs established in the MSDD, one must know what the physical attributes of the equipment are to fulfill such FRs. The Equipment Evaluation Tool presented here is intended to provide the connection between the physical attributes of a machine and how those attributes fulfill the FRs from the MSDD.

The Equipment Evaluation Tool identifies the FRs that affect equipment design and operation and then describes the physical attributes that equipment must have to satisfy these FRs to different levels of achievement. Six levels of accomplishment have been identified, from failure-to-achieve (Level 1) to full-achievement (Level 6) of the Functional Requirements from the MSDD. A rationalization of each one of the six levels of achievement and what systems typically fall into each level will be provided below. The important point to note is that the Equipment Evaluation Tool can be used to assess a particular piece or set of equipment to test how well it satisfies the FRs from the MSDD. The user can simply compare the physical attributes of the equipment with those described on the different levels of achievement presented in the evaluation tool. This comparison immediately establishes the connection between the attributes of the equipment and the goals of the manufacturing system. Based on the comparison of physical attributes of a machine against those described on the Equipment Evaluation Tool, a particular equipment design can be evaluated according to the following objectives:

1. Evaluate the current status of the design and operation of equipment by evaluating how well it satisfies the FRs from the MSDD. This evaluation can be accomplished by simply comparing the attributes of the current equipment with those described in the evaluation tool. Matching the equipment to a particular description

at a given level (from 1 to 6) gives the user a good sense of the current status of equipment design and operation from the standpoint of manufacturing system design.

2. Identify areas for improvement where the current equipment does not fully satisfy the FRs from the MSDD, and therefore focus the efforts to improve the manufacturing system on the areas that need it the most. A simple review of the scores assigned to equipment in the different evaluation categories of the evaluation tool will immediately reveal the areas in most need of improvement. The areas with the lowest scores (closer to level 1) will be the areas in most need of improvement. The same methodology can be applied if the tool is used to evaluate different pieces of equipment (or areas of a plant for example) and ratings are assigned to each one. In that case the machines (or areas of the plant) that receive the lowest scores will be the one that need most urgent action in terms of improvement efforts.

3. Indicate how equipment can fully satisfy the FRs from the MSDD, and therefore set the objectives to be achieved by the equipment design and improvement efforts. The user of the Evaluation Tool can get a clear idea of what the objectives for the design and operation of equipment are by scanning the descriptions at the highest level of achievement (level 6). These descriptions capture the ideal physical characteristics that equipment should have to support the design of the manufacturing system, and should therefore be used as goals or guidelines in the equipment design and/or improvement efforts.

4. Provide a method to track the progress of improvements in terms of equipment design and operation. The user can evaluate the same piece (or set) of equipment at different points in time and compare the resulting scores from one time period to the next. The change in the scores assigned to the equipment will reflect the improvement (or the worsening) achieved during the elapsed time.

5. Align equipment design and operation with the business objectives identified by the MSDD.

3.2.- Evaluation Criteria

As mentioned above, the objective of the Equipment Evaluation Tool is to assess how well the physical attributes of a particular piece of equipment satisfy the Functional Requirements (FRs) from the MSDD that affect equipment design and operation. Chapter 2 identified the subset of FRs from the MSDD that relate to the equipment, and those FRs will be used as the evaluation criteria in the Equipment Evaluation Tool. However, the number of FRs that relate to equipment design is a total of 22, and the authors [Gomez, Dobbs and Cochran, 2000] considered that this was a rather large number of criteria to evaluate. Therefore, in the spirit of reducing the information content of the evaluation tool without sacrificing its effectiveness, some of the criteria were consolidated to reduce the overall number of FRs to be considered.

The rationale used to consolidate the FRs was: when all (or at least most) of the sub-FRs of a particular FR affect equipment design, then the evaluation tool will use the parent FR as the evaluation criteria instead of using all of its sub-FRs. The Axiomatic Design methodology used to develop the MSDD [Suh, 1990] states that the Design Parameter (DP) that fulfills a given Functional Requirement may decompose into lower-level FRs that need to be achieved to fulfill the higher-level FR. Therefore, evaluating whether all the sub-FRs of a given FR are satisfied is the equivalent of evaluating whether the higher-level FR was satisfied, since the sub-FRs are essentially different parts of how to achieve the parent. Therefore, it is justified to use parent FRs as evaluation criteria in the Equipment Evaluation Tool when all the sub-FRs affect the equipment. The use of this rationale allows for the reduction of the number of criteria to be evaluated from 22 FRs that affect equipment design and operation to only 13 FRs, without sacrificing the effectiveness of the Evaluation Tool.

FIGURE 11 illustrates how the FRs that affect equipment design were consolidated into a smaller number of evaluation criteria using the rationale described above. It also shows how these criteria appear in the Equipment Evaluation Tool and how the criteria relate to the FRs from the MSDD.

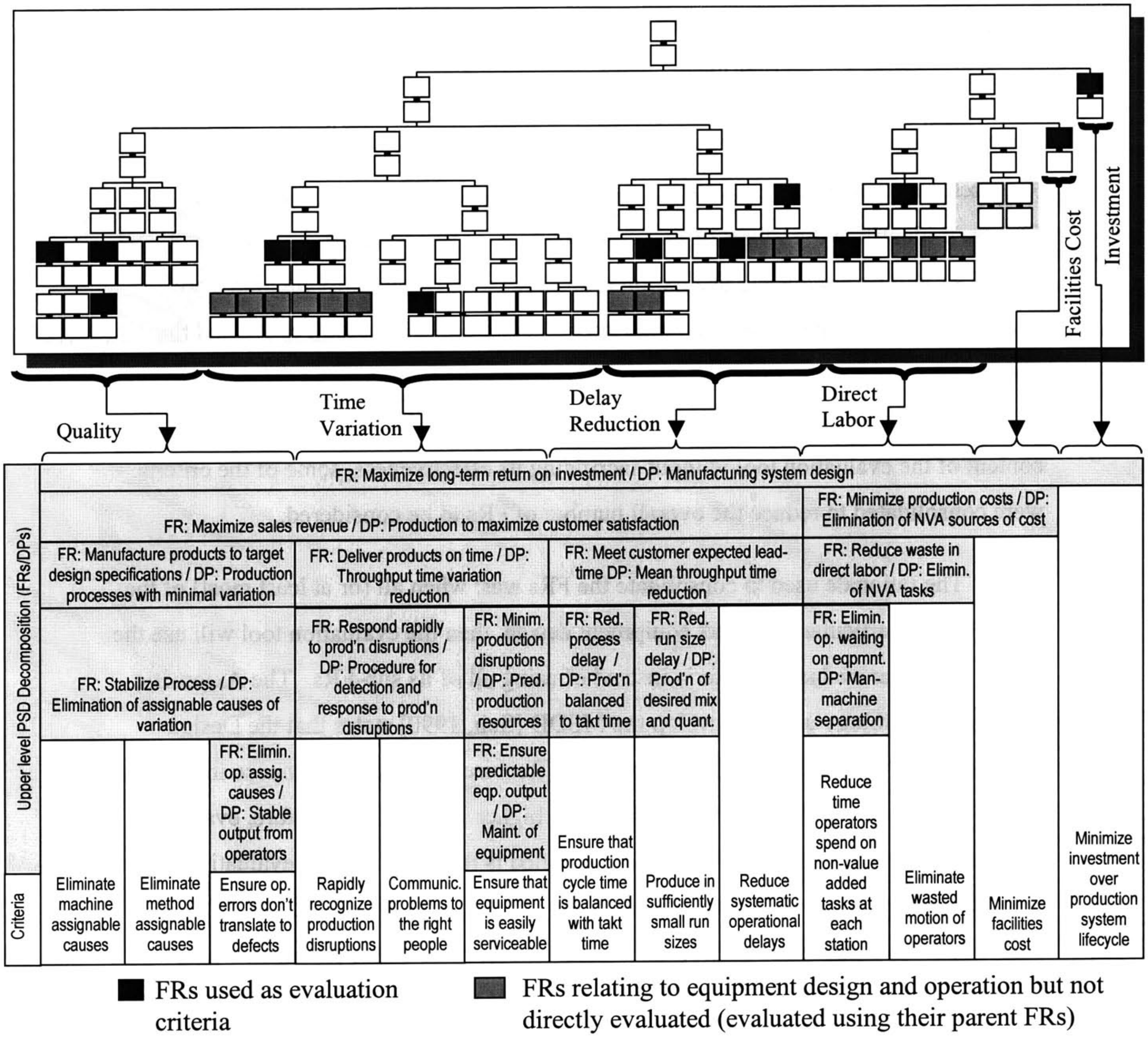


FIGURE 11: Derivation of Criteria for the Equipment Evaluation Tool from the MSDD v5.1

Notice that the FRs being considered as evaluation criteria in the Equipment Evaluation Tool do not all correspond to a particular level in the MSDD. It would be unrealistic to try to evaluate the equipment by selecting FRs at a particular level since the equipment design and operation affects various parts of the system that are defined at different levels of the MSDD. Also, it is important to note that a single machine or piece of equipment can, and generally will, be affected by several different FRs from the MSDD. Physical attributes to achieve different FRs can be combined (physical integration) and still achieve separate FRs (functional independence). The distinction between physical integration and functional independence is an important one in Axiomatic Design methodology and it applies thoroughly when designing equipment using the MSDD.

3.3.- Qualitative Evaluation

To evaluate a piece (or set) of equipment with the Equipment Evaluation Tool, the FRs have already been identified based on the discussion above and in FIGURE 11. The evaluation and grading scheme is now developed. To maintain consistency with the evaluation scheme used in the Manufacturing System Design Evaluation Tool [Chu and Cochran, 2000], the Equipment Evaluation Tool defines six levels of achievement for each FR being considered. For each FR in the Equipment Evaluation Tool, the descriptions at the six levels of achievement are consistent with a mental model of a system design as illustrated by FIGURE 12. FIGURE 12 shows a gradient of six levels of DPs corresponding to six levels of achievement relative to a given FR.

1	Level achieved by a Job Shop or Departmental Layout
2	Level achieved by Departments Arranged by Product Flow
3	Level achieved by Assembly Line or Transfer Line
4	Level achieved by Pseudo-Cell
5	Level achieved by Assembly or Machining Cells
6	Level achieved by Linked-Cell Manufacturing System

FIGURE 12: Rationalization of Achievement Levels from the Evaluation Tool

Level 1 represents a traditional manufacturing system, characterized by a job shop or departmental layout and not designed from a system perspective. Each level of achievement above level 1 describes the characteristics of equipment in systems with progressively better designs from a system perspective. Level 2 represents a system characterized by manufacturing plants arranged by departments or by product flow. Equipment that matches the descriptions provided in level 3 is usually found in systems dominated by high-speed assembly lines and/or transfer lines. Equipment in level 4 is found in plants that have started to implement the concepts of the Toyota Production System (TPS) [Monden, 1993; Ohno, 1988; Shingo, 1989] but have not mastered them yet. Level 5 represents a system characterized by the successful implementation of assembly and/or machining cells, as well as a majority of the concepts from TPS. Level 6 represents the ultimate level of achievement of a manufacturing system designed based on the MSDD, a system characterized by linked cells and the full implementation of the concepts from the Toyota Production System.

In order to evaluate a piece or series of equipment, the actual physical characteristics are matched to the descriptions under each category of the Equipment Evaluation Tool. Since it is unlikely that all machines or stations in a set of equipment will have uniform characteristics that all fall within the same level of achievement, it may be necessary to score part of the equipment being considered in one level and another portion of it at another level. The pie charts provide a method in which a portion of the equipment can score at a high level of achievement and another portion can score at a low level for a particular FR. For each FR, or column, the scores from the pie charts at all six levels should add up to 100%. FIGURE 12 shows the pie charts used in this scoring method. By using this approach, it is immediately evident which percentage of the equipment being evaluated has a high level of achievement and which percentage has a low level of achievement. Therefore the pie-chart scoring method helps to accomplish one of the objectives of the Equipment Evaluation Tool, which is to identify the equipment (or the area) in most need of improvement.

3.4.- Quantitative Evaluation

In addition to the qualitative evaluation described above, the Equipment Evaluation Tool also allows a quantitative evaluation of the criteria being considered. For each FR evaluated, a performance metric has been identified that allows a quantitative evaluation of that particular FR [Production System Design Laboratory, 2000]. This set of performance metrics is shown in FIGURE 13. The figure also shows the performance metrics for higher-level FRs, up to Return on Investment (ROI), which is the highest level metric, as a way to demonstrate the connection between the FRs being

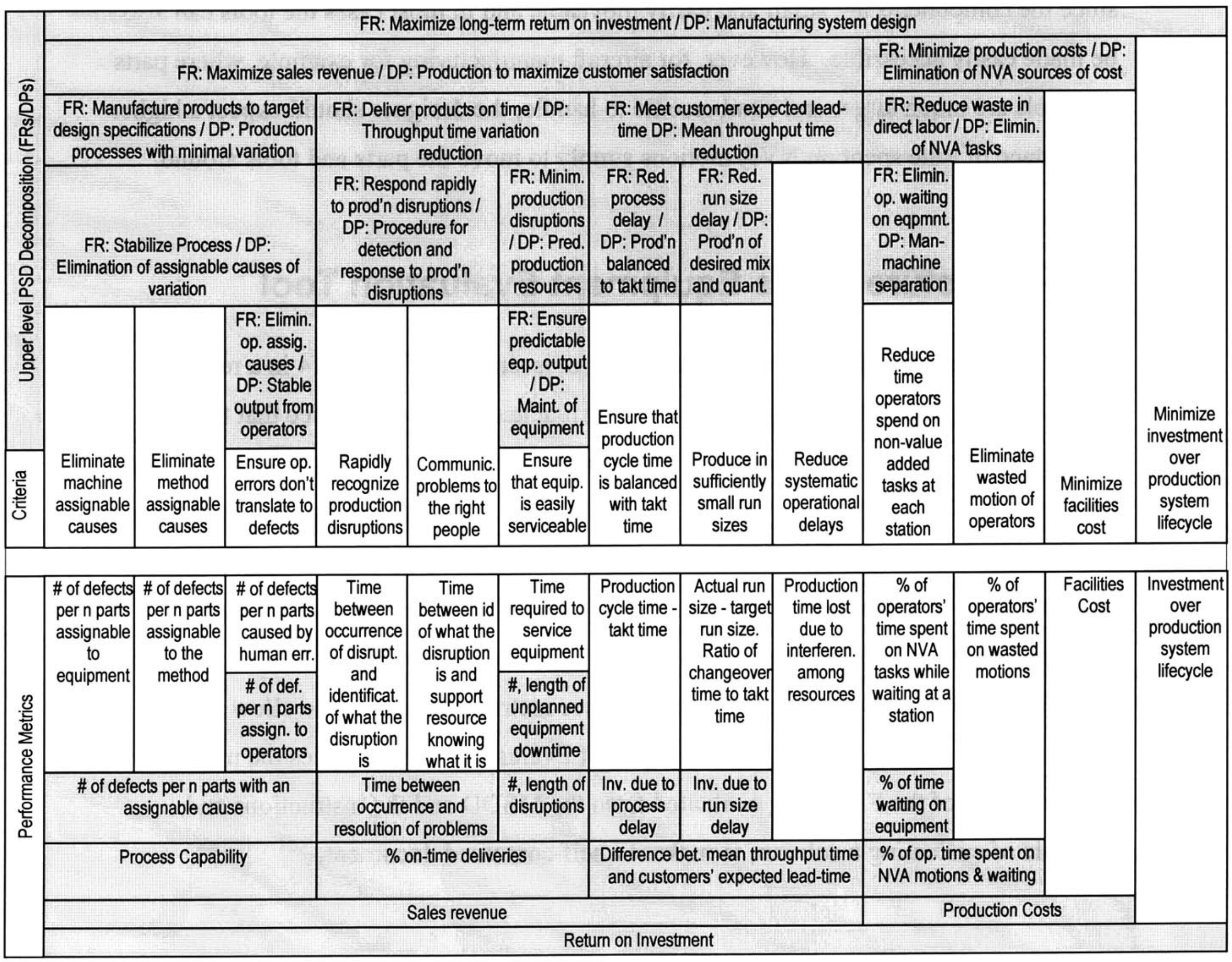


FIGURE 13: Performance Metrics from the Equipment Evaluation Tool

evaluated and the enterprise-wide objectives. It is worthwhile to mention that no target values or acceptable ranges have been set for any of the performance metrics indicated here due to the differences encountered across different industries or even across different companies for the same metrics. The designer using the Equipment Evaluation Tool must make decisions about setting the targets and acceptable ranges for the performance metrics provided, in the context of the particular industry and the application where the tool is being used. For example, regarding the manufacturing of small electronics components, the designer should expect to see a very low percentage of the operators' time wasted on non-value added (NVA) motions where there is operator interaction, since the components are small and easily moveable and in most cases the tools can also be made easily accessible. However, for aircraft manufacturing for example, where parts and tools are much larger and cumbersome to handle, the designer should expect a higher percentage of time spent on NVA motions simply to move the parts and tools around.

3.5.- Structure of the Equipment Evaluation Tool

The complete Equipment Evaluation Tool is shown in FIGURE 14 in a reduced view (due to space constraints) to present its format and structure. Notice that the Equipment Evaluation Tool consists of 13 columns, each one corresponding to one of the evaluation criteria, and each is used to assess the level of achievement of the 22 FRs from the MSDD that relate to the equipment. Each column describes the physical characteristics of equipment at each of the six levels of achievement that were also described above. The document also has a comments section to clarify the purpose and scope of each column, as well as the performance metrics for each FR to allow a quantitative evaluation. Finally, the Equipment Evaluation Tool includes the motivation, the derivation of the FRs being evaluated from the MSDD and the instructions and example of evaluating a column, to make it a self-contained document.

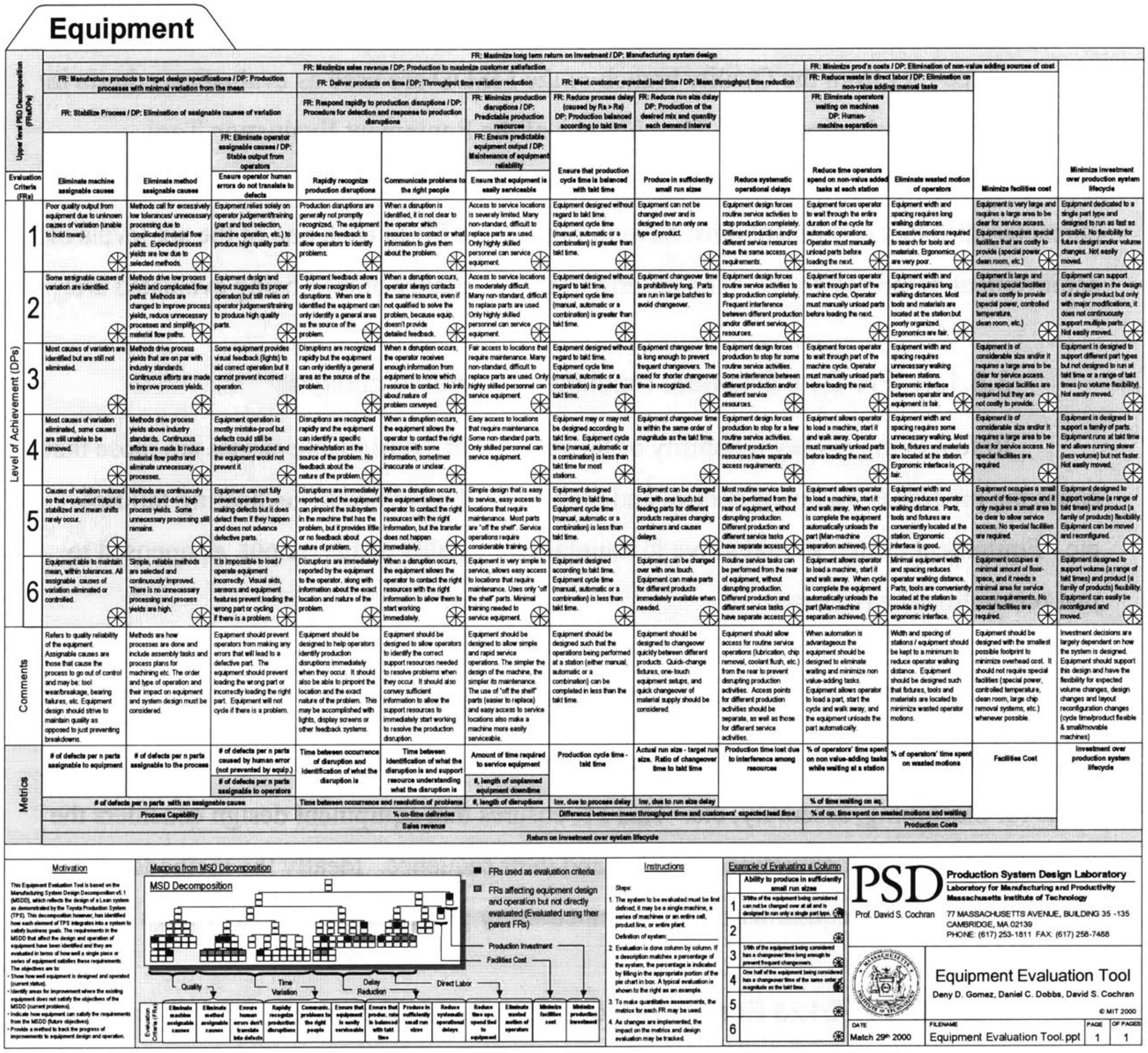


FIGURE 14: Equipment Evaluation Tool

3.5.1.- Quality

Three FRs from the Quality branch of the MSDD are used as evaluation criteria in the Equipment Evaluation Tool. The columns of the Equipment Evaluation Tool corresponding to these FRs are shown in FIGURE 15. Each column describes the physical characteristics that equipment must have to fulfill each FR to each one of the six levels of achievement described above. The criteria from the Quality branch being evaluated are:

3.5.1.1.- FR-Q11 Eliminate machine assignable causes

Refers to the quality reliability of the equipment. Assignable causes are those that cause the process to go out of control and may be: tool wear/breakage, bearing failures, etc. Equipment design should strive to maintain the quality of the output, as opposed to just preventing breakdowns.

3.5.1.2.- FR-Q13 Eliminate method assignable causes

Methods are how processes are done and include assembly tasks and process plans for machining, assembly, etc. This FR ensures that equipment design considers the impact of the types of operations selected and their sequence. Ideally the methods are simple and allow for equipment with no unnecessary processing and high process yields.

3.5.1.3.- FR-Q123 Ensure that operator human errors do not translate to defects

Equipment should prevent operators from making any errors that will lead to a defective part. The equipment should prevent loading the wrong part or incorrectly loading a part. Equipment will not cycle if there is a problem.

Evaluation Criteria (FRs)		Eliminate machine assignable causes	Eliminate method assignable causes	Ensure operator human errors do not translate to defects
Level of Achievement (DPs)	1	Poor quality output from equipment due to unknown causes of variation (unable to hold mean).	Methods call for excessively low tolerances/ unnecessary processing due to complicated material flow paths. Expected proc. yields are low due to selected methods.	Equipment relies solely on operator judgement/training (part and tool selection, machine operation, etc.) to produce high quality parts.
	2	Some assignable causes of variation are identified.	Methods drive low process yields and complicated flow paths. Methods are changed to improve proc. yields, reduce unnecessary processes and simplify material flow paths.	Equipment design and layout suggests its proper operation but still relies on operator judgement/training to produce high quality parts.
	3	Most causes of variation are identified but are still not eliminated.	Methods drive process yields that are on par with industry standards. Continuous efforts are made to improve process yields.	Some equipment provides visual feedback (lights) to aid correct operation but it cannot prevent incorrect operation.
	4	Most causes of variation eliminated, some causes are still unable to be removed.	Methods drive process yields above industry standards. Continuous efforts are made to reduce material flow paths and eliminate unnecessary processes.	Equipment operation is mostly mistake-proof but defects could still be intentionally produced and the equipment would not prevent it.
	5	Causes of variation reduced so that equipment output is stabilized and mean shifts rarely occur.	Methods are continuously improved and drive high process yields. Some unnecessary processing still remains.	Equipment cannot fully prevent operators from making defects but it does detect the occurrence and does not advance defective parts.
	6	Equipment able to maintain mean, within tolerances. All assignable causes of variation eliminated or controlled.	Simple, reliable methods are selected and continuously improved. There is no unnecessary processing and process yields are high.	It is impossible to load / operate equipment incorrectly. Visual aids, sensors and equipment features prevent loading the wrong part or cycling if there is a problem.

FIGURE 15: Columns of the Equipment Evaluation Tool from the Quality branch of the MSDD

3.5.2.- Time Variation

Three FRs from the Time Variation branch of the MSDD are used as evaluation criteria in the Equipment Evaluation Tool. The columns of the Equipment Evaluation Tool corresponding to these FRs are shown in FIGURE 16. Each column describes the physical characteristics that equipment must have to fulfill each FR to each one of the six levels of achievement described above. The criteria from the Time Variation branch being evaluated are:

3.5.2.1.- FR-R11 Rapidly recognize production disruptions

Equipment should be designed to help operators identify production disruptions immediately when they occur. Equipment should also be able to pinpoint the location and the exact nature of the problem. Lights, display screens and other feedback systems help to recognize production disruptions rapidly.

3.5.2.2.- FR-R12 Communicate problems to the right people

Equipment should be designed to allow operators to identify the correct support resources needed to resolve problems when they occur. Equipment should also convey sufficient information to allow the support resources to immediately start working to resolve the production disruption.

3.5.2.3.- FR-P121 Ensure that equipment is easily serviceable

Equipment should be designed to allow simple and rapid service operations. Ideally, equipment should be designed to be as simple as possible, since the simpler the design of the machine, the simpler its maintenance. Also, equipment should strive to use "off the shelf" parts (easier to replace) and easy access to service locations to make it more easily serviceable.

Evaluation Criteria (FRs)		Rapidly recognize production disruptions	Communicate problems to the right people	Ensure that equipment is easily serviceable
Level of Achievement (DPs)	1	Production disruptions are generally not promptly recognized. The equipment provides no feedback to allow operators to identify problems.	When a disruption is identified, it is not clear to the operator which resources to contact or what information to give them about the problem.	Access to service locations is severely limited. Many non-standard, difficult to replace parts are used. Only highly skilled personnel can service equipment.
	2	Equipment feedback allows only slow recognition of disruptions. When one is identified the equipment can only identify a general area as the source of the problem.	When a disruption occurs, operator always contacts the same resource, even if not qualified to solve the problem, because equip. doesn't provide detailed feedback.	Access to service locations is moderately difficult. Many non-standard, difficult to replace parts are used. Only highly skilled personnel can service equipment.
	3	Disruptions are recognized rapidly but the equipment can only identify a general area as the source of the problem.	When a disruption occurs, the operator receives enough information from equipment to know which resource to contact. No info about nature of problem conveyed.	Fair access to locations that require maintenance. Many non-standard, difficult to replace parts are used. Only highly skilled personnel can service equipment.
	4	Disruptions are recognized rapidly and the equipment can identify a specific machine/station as the source of the problem. No feedback about the nature of the problem.	When a disruption occurs, the equipment allows the operator to contact the right resource with some information, sometimes inaccurate or unclear.	Easy access to locations that require maintenance. Some non-standard parts. Only skilled personnel can service equipment.
	5	Disruptions are immediately reported, and the equipmt. can pinpoint the subsystem in the machine that has the problem, but it provides little or no feedback about nature of problem.	When a disruption occurs, the equipment allows the operator to contact the right resources with the right information, but the transfer does not happen immediately.	Simple design that is easy to service, easy access to locations that require maintenance. Most parts are "off the shelf". Service operations require considerable training.
	6	Disruptions are immediately reported by the equipment to the operator, along with information about the exact location and nature of the problem.	When a disruption occurs, the equipment allows the operator to contact the right resources with the right information to allow them to start working immediately.	Equipment is very simple to service, allows easy access to locations that require maintenance. Uses only "off the shelf" parts. Minimal training needed to service equipment.

FIGURE 16: Columns of the Equipment Evaluation Tool from the Time Variation branch of the MSDD

3.5.3.- Delay Reduction

Three FRs from the Delay Reduction branch of the MSDD are used as evaluation criteria in the Equipment Evaluation Tool. The columns of the Equipment Evaluation Tool corresponding to these FRs are shown in FIGURE 17. Each column describes the physical characteristics that equipment must have to fulfill each FR to each one of the six levels of achievement described above. The criteria from the Delay Reduction branch being evaluated are:

3.5.3.1.- FR-T22 Ensure that production cycle time is balanced with takt time

Equipment should be designed such that the operations being performed at a station (either manual, automatic or a combination) can be completed in less than the takt time.

3.5.3.2.- FR-T32 Produce in sufficiently small run sizes

Equipment should be designed to enable small run sizes; therefore it should changeover quickly between different products. Quick-change fixtures, one-touch equipment setups, and quick changeover of material supply should be considered to reduce the changeover time.

3.5.3.3.- FR-T5 Reduce systematic operational delays

Equipment should allow access for routine service operations (lubrication, chip removal, coolant flush, etc.) from the rear of the station to prevent disrupting production activities. Access points for different production activities should be separate.

Evaluation Criteria (FRs)		Ensure that production cycle time is balanced with takt time	Produce in sufficiently small run sizes	Reduce systematic operational delays
Level of Achievement (DPs)	1	Equipment designed without regard to takt time. Equipment cycle time (manual, automatic or a combination) is greater than takt time.	Equipment cannot be changed over and is designed to run only one type of product.	Equipment design forces routine service activities to stop production completely. Different production and/or different service resources have the same access requirements.
	2	Equipment designed without regard to takt time. Equipment cycle time (manual, automatic or a combination) is greater than takt time.	Equipment changeover time is prohibitively long. Parts are run in large batches to avoid changeover.	Equipment design forces routine service activities to stop production completely. Frequent interference between different prod'n and/or different service resources.
	3	Equipment designed without regard to takt time. Equipment cycle time (manual, automatic or a combination) is greater than takt time.	Equipment changeover time is long enough to prevent frequent changeovers. The need for shorter changeover time is recognized.	Equipment design forces production to stop for some routine service activities. Some interference between different production and/or different service resources.
	4	Equipment may or may not be designed according to takt time. Equipment cycle time (manual, automatic or a combination) is less than takt time for most stations.	Equipment changeover time is within the same order of magnitude as the takt time.	Equipment design forces production to stop for a few routine service activities. Different production resources have separate access requirements.
	5	Equipment designed according to takt time. Equipment cycle time (manual, automatic or a combination) is less than takt time.	Equipment can be changed over with one touch but feeding parts for different products requires changing containers and causes delays.	Most routine service tasks can be performed from the rear of equipment, without disrupting production. Different production and different service tasks have separate access
	6	Equipment designed according to takt time. Equipment cycle time (manual, automatic or a combination) is less than takt time.	Equipment can be changed over with one touch. Equipment can make parts for different products immediately available when needed.	Routine service tasks can be performed from the rear of equipment, without disrupting production. Different production and different service tasks have separate access

FIGURE 17: Columns of the Equipment Evaluation Tool from the Delay Reduction branch of the MSDD

3.5.4.- Direct Labor

Two FRs from the Direct Labor branch of the MSDD are used as evaluation criteria in the Equipment Evaluation Tool. The columns of the Equipment Evaluation Tool corresponding to these FRs are shown in FIGURE 18. Each column describes the physical characteristics that equipment must have to fulfill each FR to each one of the six levels of achievement described above. The criteria from the Direct Labor branch being evaluated are:

3.5.4.1.- FR-D11 Reduce time operators spend on non-value added tasks at each station

When automation is advantageous the equipment should be designed to prevent tying the operator to the station waiting for an automatic cycle to be completed. The equipment should allow the operator to load a part, start the cycle and walk away, and the equipment will unload the part automatically when finished.

3.5.4.2.- FR-D2 Eliminate wasted motion of operators

The width and spacing of stations/equipment should be kept to a minimum to reduce the operators' walking distance. Equipment should be designed such that fixtures, tools and materials are located to minimize wasted operator motions.

Evaluation Criteria (FRs)		Reduce time operators spend on non-value added tasks at each station	Eliminate wasted motion of operators
Level of Achievement (DPs)	1	Equipment forces operator to wait through the entire duration of the cycle for automatic operations. Operator must manually unload parts before loading the next.	Equipment width and spacing requires long walking distances. Excessive motions required to search for tools and materials. Ergonomics are very poor.
	2	Equipment forces operator to wait through part of the machine cycle. Operator must manually unload parts before loading the next.	Equipment width and spacing requires long walking distances. Most tools and materials are located at the station but poorly organized. Ergonomics are fair.
	3	Equipment forces operator to wait through part of the machine cycle. Operator must manually unload parts before loading the next.	Equipment width and spacing requires unnecessary walking between stations. Ergonomic interface between operator and equipment is fair.
	4	Equipment allows operator to load a machine, start it and walk away. Operator must manually unload parts before loading the next.	Equipment width and spacing requires some unnecessary walking. Most tools, fixtures and materials are located at the station. Ergonomic interface is fair.
	5	Equipment allows operator to load a machine, start it and walk away. When cycle is complete the equipment automatically unloads the part (Man-machine separation achieved).	Equipment width and spacing reduces operator walking distance. Parts, tools and fixtures are conveniently located at the station. Ergonomic interface is good.
	6	Equipment allows operator to load a machine, start it and walk away. When cycle is complete the equipment automatically unloads the part (Man-machine separation achieved).	Minimal equipment width and spacing reduces operator walking distance. Parts, tools are conveniently located at the station to provide a highly ergonomic interface.

FIGURE 18: Columns of the Equipment Evaluation Tool from the Direct Labor branch of the MSDD

3.5.5.- Facilities Cost and Production Investment

The Facilities Cost FR and the Production Investment FR from the MSDD are both used as evaluation criteria in the Equipment Evaluation Tool. The columns of the Equipment Evaluation Tool corresponding to these FRs are shown in FIGURE 19. Each column describes the physical characteristics that equipment must have to fulfill each FR to each one of the six levels of achievement described above. The Facilities Cost and Production Investment FRs being evaluated are:

3.5.5.1.- FR123 Minimize facilities cost

Equipment should be designed with the smallest possible footprint to minimize overhead cost. It should not require special facilities (special power, controlled temperature, clean room, large chip removal systems, etc.) whenever possible.

3.5.5.2.- FR13 Minimize investment over production system lifecycle

Investment decisions are largely dependent on how the system is designed. Equipment should support the system design and have the flexibility for expected volume changes, design changes and layout reconfiguration changes (cycle time; product flexibility and small/movable machines).

Evaluation Criteria (FRs)		Minimize facilities cost	Minimize investment over production system lifecycle
Level of Achievement (DPs)	1	Equipment is very large and requires a large area to be clear for service access. Equipment requires special facilities that are costly to provide (special power, clean room, etc.)	Equipment dedicated to a single part type and designed to run as fast as possible. No flexibility for future design and/or volume changes. Not easily moved.
	2	Equipment is large and requires special facilities that are costly to provide (special power, controlled temperature, clean room, etc.)	Equipment can support some changes in the design of a single product but only with major modifications, it does not continuously support multiple parts. Not easily moved.
	3	Equipment is of considerable size and/or it requires a large area to be clear for service access. Some special facilities are required but they are not costly to provide.	Equipment is designed to support different part types but not designed to run at takt time or a range of takt times (no volume flexibility). Not easily moved.
	4	Equipment is of considerable size and/or it requires a large area to be clear for service access. No special facilities are required.	Equipment is designed to support a family of parts. Equipment runs at takt time and allows running slower (less volume) but not faster. Not easily moved.
	5	Equipment occupies a small amount of floor-space and it only requires a small area to be clear to allow service access. No special facilities are required.	Equipment designed to support volume (a range of takt times) and product (a family of products) flexibility. Equipment can be moved and reconfigured.
	6	Equipment occupies a minimal amount of floor-space, and it needs a minimal area for service access requirements. No special facilities are required.	Equipment designed to support volume (a range of takt times) and product (a family of products) flexibility. Equipment can easily be reconfigured and moved.

FIGURE 19: Columns of the Equipment Evaluation Tool from the Facilities Cost and Production Investment branches of the MSDD

3.6.- Summary

This chapter presented an Equipment Evaluation Tool that can be used to assess how well the design and operation of a particular piece (or set) of equipment within a manufacturing enterprise supports the design of the manufacturing system. The Equipment Evaluation Tool is based on the Manufacturing System Design Decomposition v5.1 (MSDD) introduced in Chapter 1. It identifies which Functional Requirements from the MSDD relate to equipment design and operation and which physical characteristics the equipment should have to satisfy these requirements. The Equipment Evaluation Tool allows a qualitative evaluation of the equipment in a gradient of 6 levels of achievement by comparing the physical attributes of the equipment to the descriptions under each one of the levels. The Equipment Evaluation Tool also allows a quantitative evaluation by using the performance metrics for each FR being assessed.

The Equipment Evaluation Tool can be very valuable to a manufacturing enterprise since it serves to measure how well the current design and operation of equipment supports the production system design. The tool can also be very useful in providing a guideline or set of objectives for the improvement of current equipment or the design of new equipment. Another application is to track the progress of a system as the equipment design changes.

It is important to note that the concepts and descriptions in the Equipment Evaluation Tool are intentionally general in nature, and therefore might not apply exactly to every industry or every manufacturing operation. When using the Equipment Evaluation Tool it might be useful to alter some of the descriptions and/or performance metrics to suit the particular industry or system under evaluation.

Chapter 4: Case Study of Visteon Indianapolis Steering Gear Assembly

This chapter presents the work done in equipment design to support manufacturing system design at a particular automotive component manufacturing plant. This case study is intended to be an example of the application of the equipment design principles outlined in Chapters 1 and 2 in a practical context. The project involved concept-level design of equipment to assemble automotive components, and therefore lent itself to the application of the equipment design framework presented above. Throughout the chapter, it will be shown how the particular automotive components in question (rack and pinion steering gears) have traditionally been assembled and why. Then a proposed design for an assembly system for these components will be presented that incorporates the concepts from Chapters 1 and 2. This case study will also allow the use of the Equipment Evaluation Tool introduced in Chapter 3 as a design tool. It will illustrate how the Equipment Evaluation Tool can help assess the problem areas in the existing assembly systems, how it is useful when designing new assembly systems, and how it can lead to designs that better accomplish the Functional Requirements established in the MSDD.

The work presented in this chapter was completed in the period from October 1998 to May 2000. During this period the author worked closely with engineers and management from the Visteon Indianapolis plant, and also in collaboration with people from the Production System Design (PSD) Laboratory at the Massachusetts Institute of Technology. The author would like to acknowledge the sponsorship of Visteon that made this project possible and the help from the people at Visteon Indianapolis: Bill Ramirez, Jeff Clark, Greg Fisher, Steve Watkins, Stuart Anderson and many others. Also, the collaboration with Prof. David Cochran and graduate students Daniel Dobbs and Guillermo Oropeza from the PSD Lab has been of critical importance for the completion of the work.

4.1.- The Plant

The manufacturing facility that this case study refers to is a Visteon Automotive Systems plant located in Indianapolis, IN. Visteon is a supplier of components and subsystems to the automotive industry that used to be a division of Ford Motor Company but is now in the process of becoming a separate company and securing new customers besides Ford.

The Visteon Indianapolis plant is approximately 2 million ft^2 in size and it employs about 3000 people. It manufactures steering components for vehicles and it can manufacture most of the subcomponents needed to supply complete steering subsystems. The plant currently supplies vehicle assembly plants from Ford North America, Ford Europe and Ford South America. The plant is comprised of five divisions:

- Rack and pinion steering gears.
- Rotary valve steering gears.
- Power steering pumps.
- Steering columns.
- Valve subassemblies (for rack and pinion steering gears).

4.2.- The Product

Rack and Pinion Steering Gears are one of the critical components in the steering subsystem of a vehicle. The gear is the component that actually converts the rotational motion of the steering wheel to the translation motion that actuates the wheels. The conversion is done mechanically but it is hydraulically assisted to reduce the force that the driver must exert onto the steering wheel. FIGURE 20 shows a typical Rack and Pinion Steering Gear. The steering pump interfaces with the steering gear and provides it with pressurized fluid used to accomplish the hydraulic assistance. It is important to note that as a safety consideration, even when the pump does not provide pressurized fluid (either because the engine is off or because it malfunctions) the gear can still be used to steer the vehicle since it is essentially a mechanical component. The steering gear also interfaces with the steering column, which transmits the torque from the steering wheel to the steering gear and in some cases allows adjustment of the position of the steering wheel for driver comfort.

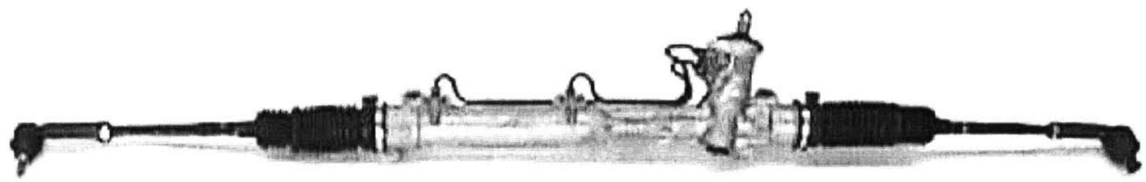


FIGURE 20: Rack and Pinion Steering Gear

Each steering gear model is different from the next in some way, however they all share certain characteristics and similarities, particularly in the major component parts. FIGURE 21 is an exploded view of one of the Rack and Pinion Steering Gears manufactured at the Visteon Indianapolis plant and it shows how the different components are assembled into the finished product. Most steering gears have the following major components:

- Housing (1-piece cast housings are shown in FIGURE 20 and FIGURE 21, but housings composed of 2 or 3 parts are also used).
- Rack bar.
- Valve subassembly.
- Tie rods / Tie rod ends.
- Boots (bellows).
- Hydraulic fluid lines (Turnlines).
- Yoke plug and components.
- Bushings and bearings.
- Seals and clamps.
- Fittings and fasteners.

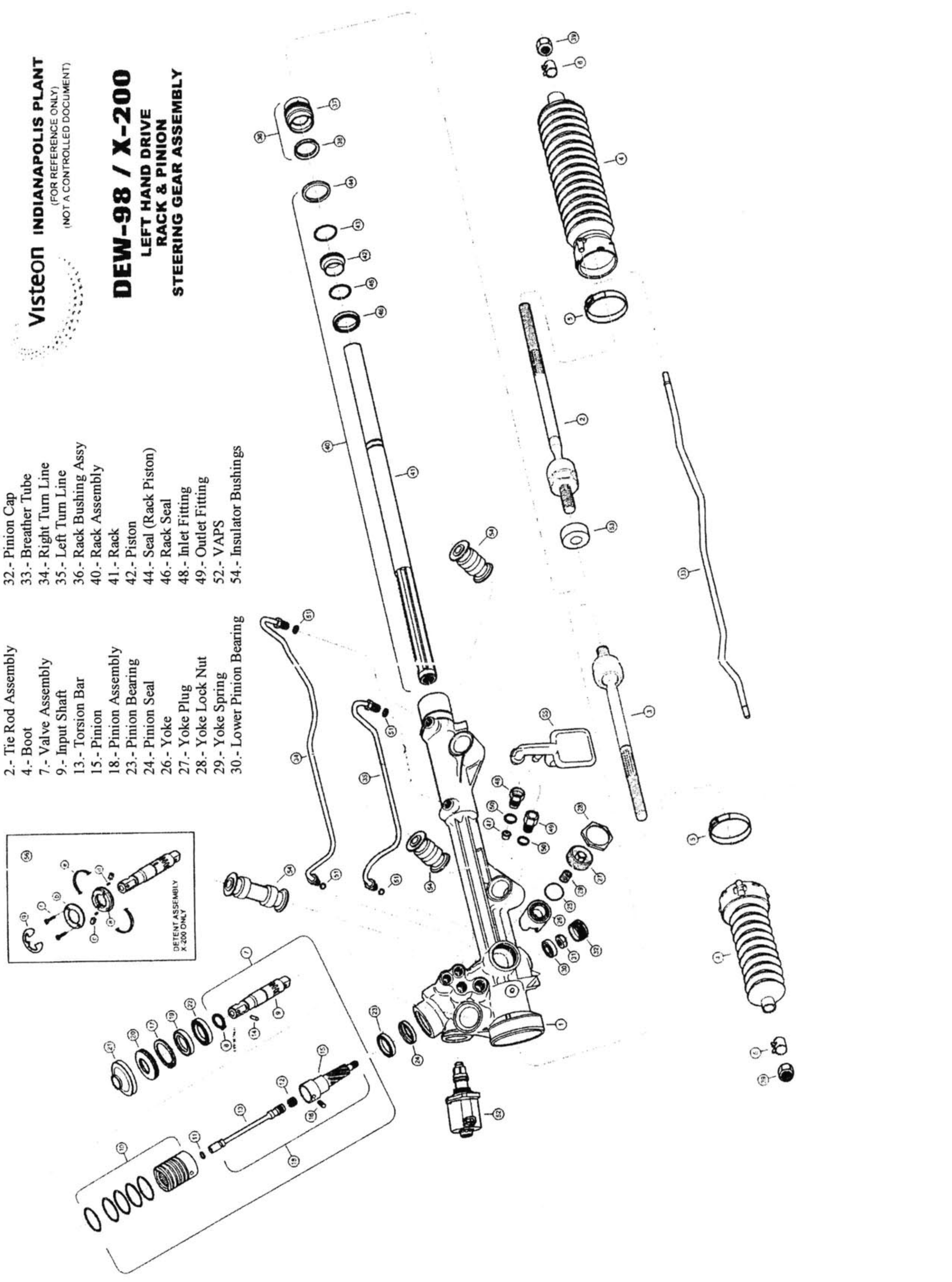


FIGURE 21: Exploded View of a Steering Gear [Visteon Indianapolis Plant, 1999]

The final assembly process for Rack and Pinion Steering Gears consists mainly of putting together all these components in the correct order. The assembly process is mostly manual, with operations which require the dexterity and flexibility of humans to put together the respective parts, although some tasks are mechanically assisted or semi-automated due to the large forces required. The final assembly of Rack and Pinion Steering Gears could potentially be fully automated, although that generally has not been done due to the complexity and costs that would be associated with the equipment needed to do so. During final assembly the components are also tested to ensure that they will work properly, and these tests are usually performed by automated equipment. A typical sequence of the major assembly operations for a Rack and Pinion Steering Gear is shown in TABLE 3, together with a brief description of the nature of each operation. It is important to note that the sequence of operations may vary slightly from gear to gear but the sequence shown provides a good guideline for a typical final assembly process.

MAJOR ASSEMBLY OPERATION	TYPE
Clamp housing to pallet/fixture	Manual
Install housing bushings	Mechanically Assisted
Install hydraulic fluid lines (turnlines)	Mechanically Assisted
Install valve (lower) bearings and seals	Semi-Automatic
Insert rack	Semi-Automatic
Install valve subassembly	Manual
Install rack bushing	Mechanically Assisted
Install valve (upper) bearings and seals, and nut and cap	Mechanically Assisted
Install yoke plug and components	Mechanically Assisted
Air leak test	Automatic
Burnish (break-in the mechanical gears)	Automatic
Final set (of yoke to provide correct steering resistance)	Automatic
Functional Test	Automatic
Install tie rods (and outer tie rods if applicable)	Semi-Automatic
Install Boots (Bellows), clamps and breather tube	Manual
Inspect and pack into shipping containers	Manual

TABLE 3: Typical Major Assembly Operations for a Rack and Pinion Steering Gear

4.3.- The Project

The project at the Visteon Indianapolis facility focused on designing several production systems for the final assembly of Rack and Pinion Steering Gears. An important focus throughout the project was to migrate from the traditional mass production assembly systems to assembly systems that incorporate the concepts from the Production System Design Framework introduced in Chapter 1. Throughout the project the author was involved in the design and/or implementation of a total of four assembly systems. Each new system improved on the previous one and attempted to solve some of the problems encountered by its predecessors. Specifically, the four assembly systems that were implemented at the Visteon Indianapolis facility were the following; listed by the internal name given to the program:

- DEW 98 / X-200: Steering gears for the Lincoln LS and Jaguar S-type.
- U-152: Steering gears for the Ford Explorer.
- U-204: Steering gears for a new vehicle not yet available in the market.
- U-222: Steering gears for the Ford Expedition and Lincoln Navigator.

Chronologically the DEW 98 assembly cell started production in 1998, the U-152 and U-204 cells started production at about the beginning of 2000, and the U-222 program is scheduled to start full production by 2002. Once the DEW 98 line was operational, several problems were identified that were inherent in the design of the equipment and needed to be addressed in the later programs. From the lessons learned from the DEW 98, several objectives were set for the design of equipment for future programs. These objectives were in addition to the requirements imposed by the MSDD and were intended to solve specific problems at the Indianapolis plant, particularly:

- Design equipment that allows the optimization of operator's motions.
- Minimize the width of stations/aisle.
- Minimize protrusions of the equipment into the operator's workspace.
- Integrate the design of containers and material replenishment hardware with the design of each station in the cell.

Also, during the design process for the DEW 98 assembly system equipment, the author and the team from MIT identified the need to provide the machine builder (provider of equipment for Visteon Indianapolis) with detailed drawings of the proposed equipment. These detailed drawings were necessary to demonstrate how some of the concepts from the Production System Design Framework could be physically implemented, and also to demonstrate how the design of the equipment could achieve the specific objectives mentioned above. The detailed drawings of the equipment provided to Visteon Indianapolis during the design process of the assembly cell for the U-222 gear will be introduced below.

For the purposes of this case study, one of the assembly systems typically found in the Indianapolis plant before this project started (WIN 88) will be compared against the assembly system designed for the U-222 project. The WIN 88 assembly system was selected because it is a typical example of the assembly lines currently in use at the plant, high-speed asynchronous assembly lines designed with a specific set of performance metrics in mind, an idea that will be revisited on the next section. The U-222 project was selected because it is the latest of the systems designed in the context of this project and its design provides solutions to many of the problems encountered by its predecessors. Also, the U-222 assembly project is the one for which the author (together with Guillermo Oropeza and Prof. David Cochran) had the greatest opportunity to provide input during the design process. For this project the author (together with Oropeza and Cochran) was able to provide detailed drawings that showed the conceptual design that best satisfied the FRs from the MSDD related to the equipment. In previous projects there was little opportunity to provide as detailed feedback during the design process. Finally, the U-222 assembly system is, among the several new cells at Visteon Indianapolis, the one that best incorporates the concepts and ideas relating to equipment design from the Production System Design Framework (Refer to Chapters 1 and 2) and as such it is the best candidate for a comparison against a traditional assembly system.

4.4.- Current Assembly System

The WIN 88 assembly system was selected as a point of comparison because it is a typical example of the assembly lines currently in use at the Visteon Indianapolis plant. The WIN 88 line is a high-speed asynchronous assembly line that provides steering gears for the Ford Taurus, Ford Windstar, Mercury Sable and Lincoln Continental. The WIN 88 line is a good illustration of an assembly line in a mass production system that has evolved and adapted to optimize performance metrics that do not necessarily correspond to enterprise objectives [Cochran and Dobbs, 2000]. Particularly, the critical performance metrics that are optimized in traditional mass production manufacturing environments are: machine utilization and direct labor costs. In this environment, the equipment is seen as the most valuable asset and its utilization is driven to the maximum possible. Also, direct labor costs are traditionally considered to be the highest cost drivers and therefore the mentality is to reduce them as much as possible by reducing manual content for each operation and reducing the cycle time so that operators can repeat the same small task numerous times during their work period. The drive to optimize these performance metrics leads to the design of equipment with very fast cycle times and minimized work content at each station, which typically translates into increased automation [Cochran and Dobbs, 2000].

The WIN 88 line aggregates demand from several customers to achieve a cycle time of 12 seconds; it supplies steering gears to four different vehicle programs (Ford Taurus, Ford Windstar, Mercury Sable and Lincoln Continental). Each of these four vehicles is assembled at one of four different vehicle assembly plants. Cochran and Dobbs summarize their observations on the thought process leading to the design of high-speed assembly lines similar to the WIN 88 line as follows:

> [Plants aggregate demand] from several customers in order to reduce direct labor costs and maximize machine utilization. The result is that one assembly line is designed to meet the aggregate demand from all of the customers. This practice prevents the assembly line from operating at <u>one</u> customer's takt time and requires the assembly lines to have very fast cycle times.
>
> Automated machines are designed for high-speed and the work content at manual stations is small. An operator must remain at each manual station while the line is

> running. If demand drops, it may be possible to run the line at less than full speed, but there is no benefit in doing so because the number of workers cannot be reduced. Therefore, the design causes labor cost to be fixed. [Cochran and Dobbs, 2000]

FIGURE 22 shows a diagram of the WIN 88 assembly line. Notice that there are operators assigned to particular stations, those where manual work is to be completed, and they work exclusively at that station. Also notice the presence of repair loops and a repair bench built into the design of the line, as well as operators assigned specifically to the repair areas, which denotes the acceptance of the idea that a high number of defective parts will be produced and will need to be repaired. Finally, notice the overall size of the assembly line, in comparison with the size of the proposed assembly cell that will be presented below.

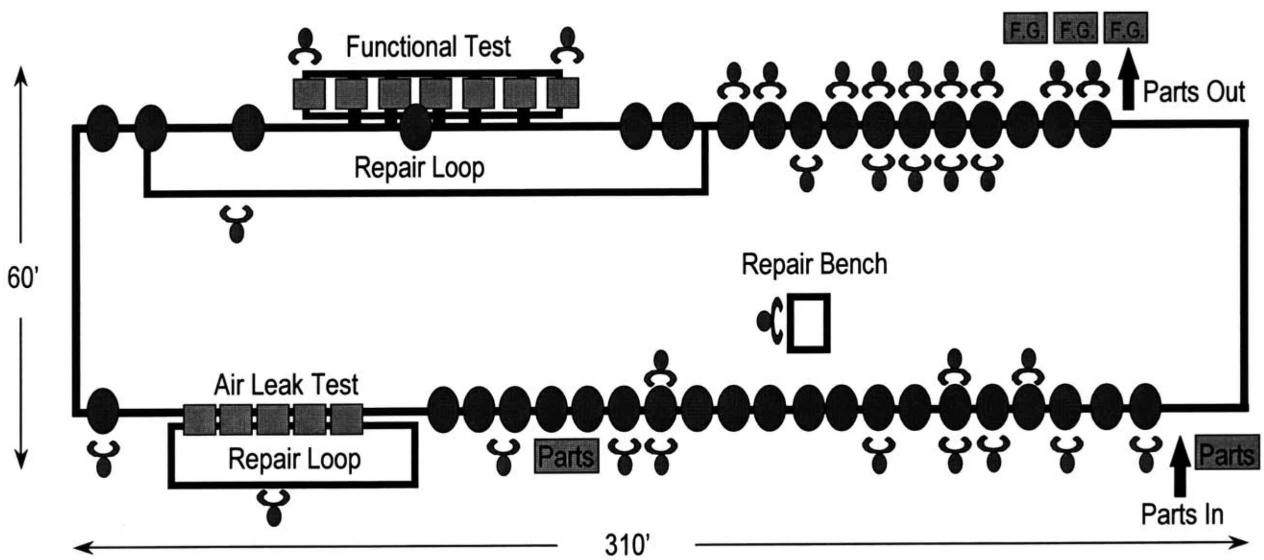


FIGURE 22: WIN 88 Assembly Line [Cochran and Dobbs, 2000]

TABLE 4 summarizes some relevant performance metrics for the WIN 88 assembly line. The fast cycle time, high level of inventory, long throughput time and minimized manual work content (reflected in the relatively low amount of operator time required to assemble the product) are all characteristics of traditional mass production environments.

PERFORMANCE METRIC	WIN 88 ASSEMBLY LINE
Production volume per year	910,000 parts
Number of shifts per day	2
Number of models produced in assembly system	4
Production cycle time	12 seconds
Overall Equipment Effectiveness (OEE)	~ 85%
Work in process	270 parts
Finished goods inventory	13,000 parts
Floor space consumed	20,000 ft^2
Total distance parts travel	720 ft
Number of direct workers	32
Number of repair workers	3
Operator time required per part	12.3 minutes/part
Throughput time of system	46 hours (incl. machining)
Material replenishment rate	Unpredictable

TABLE 4: Relevant Performance Metrics for the WIN 88 Assembly Line

4.5.- Assessment of the Current Assembly System Using the Equipment Evaluation Tool

An evaluation of the WIN 88 line using the Equipment Evaluation Tool introduced in Chapter 3 yields the results shown below in FIGURE 23. The average level of achievement across all the FRs being evaluated is only 2.26. According to the qualitative evaluation criteria illustrated in FIGURE 12 (page 55), a 2.26 achievement level corresponds to a system somewhere in between a plant arranged by departments or product flow and a system dominated by high-speed assembly lines and/or transfer lines, which is an accurate description of the Visteon Indianapolis plant. Notice that 2.26 is a straight average of the levels of achievement across all the columns, which gives equal weight to all the FRs from the MSDD that relate to equipment design and that are being evaluated. It is conceivable that for other applications the user of the Equipment Evaluation Tool might assign different weights to the different columns depending on the relative importance of each FR being evaluated, and then calculate a weighted average.

	FRs from Equipment Evaluation Tool												
	FR-Q11	FR-Q13	FR-Q123	FR-R11	FR-R12	FR-P121	FR-T22	FR-T32	FR-T5	FR-D11	FR-D2	FR123	FR13
Level of Achievement 1	37.5%	50%	37.5%	50%	50%	12.5%	75%			50%			
2	37.5%	25%	50%	25%	25%	12.5%			12.5%	50%	50%	50%	
3	25%	25%	12.5%	25%	25%	75%		100%	62.5%		25%	25%	100%
4							25%		25%		25%	25%	
5													
6													
Sum	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Average Level	1.88	1.75	1.75	1.75	1.75	2.63	1.75	3.00	3.13	1.50	2.75	2.75	3.00
Average Level of Achievement Across All Columns: **2.26**													

FIGURE 23: Assessment of the WIN 88 Line Using the Equipment Evaluation Tool

The FR with the lowest average level of achievement is FR-D11: Reduce time operators spend on non-value added tasks at each station. Such a low score reflects the fact that in the WIN-88 line operators are tied to individual stations and are not able to perform multiple tasks. The scores in the Quality section of the Equipment Evaluation Tool (FR-Q11, FR-Q13 and FR-Q123) are also very low across the board, which reflects the mentality behind the design of the WIN 88 line; the acceptance of the idea that a high number of defects will be produced and repair loops and repair operators will be needed to handle them. The low scores in the Time Variation branch (FR-R11, FR-R12 and FR-P121) are a consequence of the high variation in the throughput time of parts in the WIN 88 line due to the multiple flow paths a part can follow since the testing machines are in parallel and since the parts can be diverted to the repair loops.

4.6.- Proposed Assembly System

The U-222 program will provide steering gears for the Ford Expedition and Lincoln Navigator, and it is intended to start production by 2002. The assembly system presented here is the system proposed by the author together with Guillermo Oropeza and Prof. David Cochran to Visteon Indianapolis, and therefore the actual production system that is implemented for the U-222 program might differ significantly from what is presented here. Still, the proposal is detailed and accurate enough to grant its analysis and to allow a meaningful comparison with the WIN 88 line. The proposed U-222 assembly system is an assembly cell, with the workstations arranged in two parallel rows. The equipment is designed such that all production activities can be completed from inside the two parallel rows of equipment, therefore all of the operators work from inside the cell. Also, the equipment is designed so that the replenishment of component parts, as well as routine equipment maintenance, is performed from the outside of the cell to prevent disruptions to the production activities. FIGURE 24 shows a layout of the U-222 assembly cell.

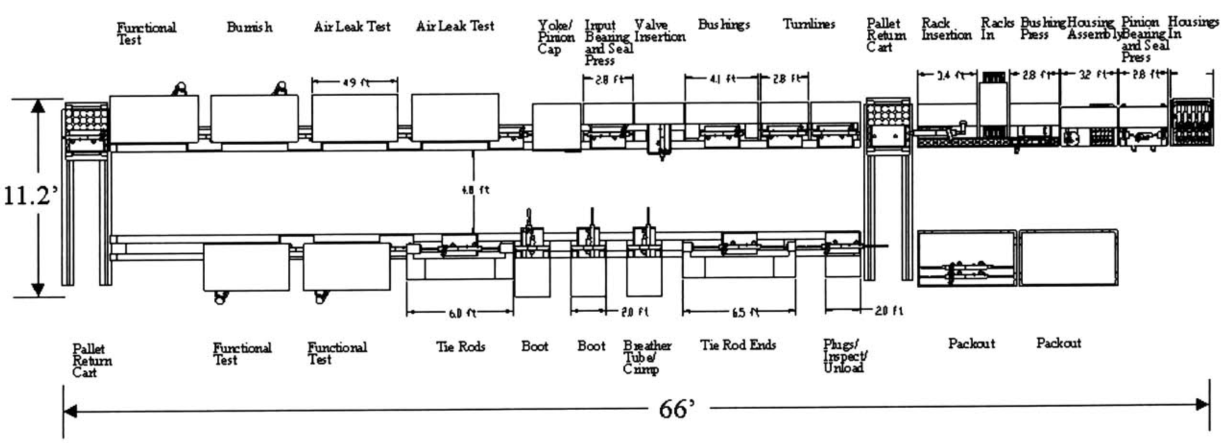


FIGURE 24: Layout of U-222 Assembly Cell

The design of the U-222 assembly cell represents a radical departure from the mentality dominating the design of the WIN 88 line. In the WIN 88 line the drive was to optimize a specific set of performance metrics, particularly machine utilization and direct labor costs. The U-222 cell was designed to satisfy the FRs from the MSDD that relate to equipment design and operation (refer to Chapter 2). The objectives and performance metrics that affect the design and operation of the equipment are derived directly from the enterprise objectives, and therefore the equipment enables the production system to achieve these high-level goals [Cochran and Dobbs, 2000]. The U-222 cell is focused on producing parts for only two customers, which enables the lowest possible inventory level. In turn, "the decreased inventory results in shorter response and throughput times, allowing immediate feedback and enabling faster problem resolution" [Cochran and Dobbs, 2000]. TABLE 5 shows a comparison of relevant performance metrics between the WIN 88 line and the U-222 assembly cell. The performance metrics for the U-222 cell have been projected (since the system is not yet operational) based on the proposed design and the performance of similar systems implemented elsewhere. Notice that a cycle time of 29 seconds for the U-222 cell is still not ideal because it still is a short time to enable the separation of the worker from the machine, but it was a compromise

PERFORMANCE METRIC	**WIN 88 LINE**	**U-222 CELL (PROJECTIONS)**
Production volume per year	910,000 parts	380,000 parts
Number of shifts per day	2	2
Number of models produced in system	4	2
Production cycle time	12 seconds	29 seconds
Overall Equipment Effectiveness	~ 85%	85%
Work in process	270 parts	30 parts
Finished goods inventory	13,000 parts	5,000 parts
Floor space consumed	20,000 ft^2	1,500 ft^2
Total distance parts travel	720 ft	190 ft
Number of direct workers	32	12
Number of repair workers	3	0
Operator time required per part	12.3 minutes/part	13 minutes/part
Throughput time of system	46 hours (incl. mach.)	40 minutes
Material replenishment rate	Unpredictable	2 hours

TABLE 5: Comparison of Relevant Performance Metrics for the WIN 88 Assembly Line and the U-222 Assembly Cell

adopted by the Visteon Indianapolis management in combining the demand from two vehicle assembly programs to reduce the initial investment. The design of equipment from a systems perspective for the U-222 assembly cell results in reduced inventory and reduced total distance that parts travel, which in turn enables the system to be more responsive, which is reflected in the reduced throughput time of the system. Also notice the reduced overall size of the U-222 cell in comparison with the WIN 88 line. FIGURE 25 shows the difference in the overall size of the assembly systems being compared.

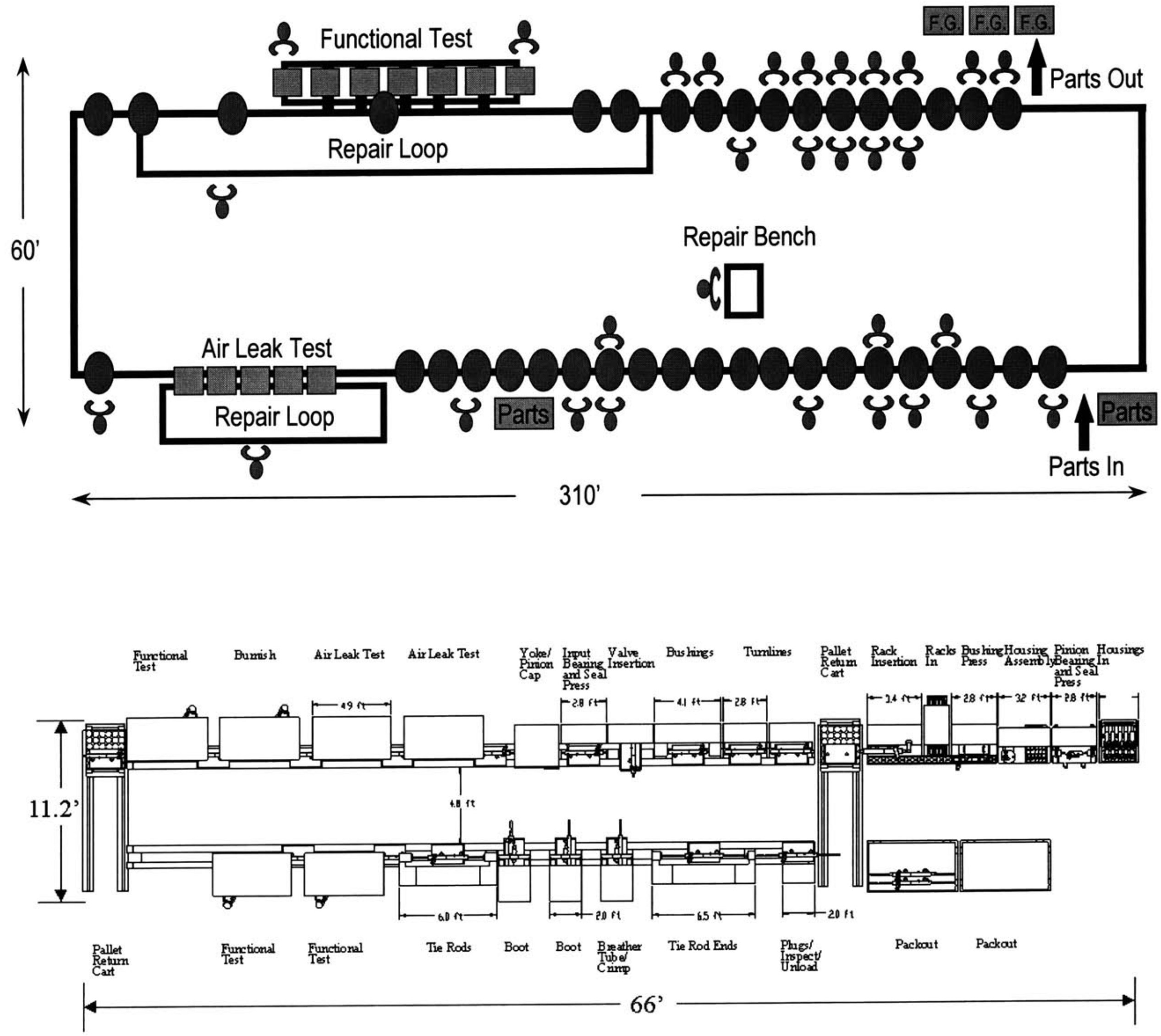


FIGURE 25: Size Comparison Between the WIN 88 Line (Top) and the U-222 Assembly Cell (Bottom)

The figures in the next several pages (FIGURE 26 through FIGURE 31) show detailed views of the proposed equipment designed for the U-222 assembly cell. Notice in these figures the compact size of the stations and how close they are placed to each other. This design reduces operator motions and enables the workers to operate multiple stations in their work routines, in other words it separates the operators from individual stations in the cell. Also, each station was designed to allow the operator to load a part, start the machine cycle by activating a walk-away switch and move on to a different station while the equipment cycles (with the exception of the stations where the operation is entirely manual). The idea is to achieve the separation of the operator from the machine, such that operators can operate several stations by following a work pattern (work-loop). The benefits of separating the operator from the individual stations are:

- Volume flexibility: The work patterns can be changed depending on volume fluctuations, which gives the system increased volume flexibility. If demand for the product increases, more workers can be added to operate shorter work-loops in a faster takt time and therefore accommodate the increased demand. If demand drops then workers can be removed and the stations can be operated in longer work-loops in a shorter takt time to accommodate the decreased demand.
- Operators can help each other when non-standard work occurs. In the case when defects are produced or machines break down, or some other non-standard activity occurs, the operators are not tied to their machine and therefore they are free to operate multiple stations as needed to resolve the disruption.
- The work can be more easily balanced among different operators. Since stations are close together and the operators are able to operate multiple ones at once, the work balancing becomes simply a task of defining the standard work combination for the operators. There is no longer any need to move equipment or to change the processing methods to balance the operator work.
- Quality problems are immediately obvious since any disruption at a station affects the other stations directly. Since disruptions can be more easily identified, more effort can be placed into resolving these disruptions.
- The system is improvable since it is more flexible disruptions are evident.

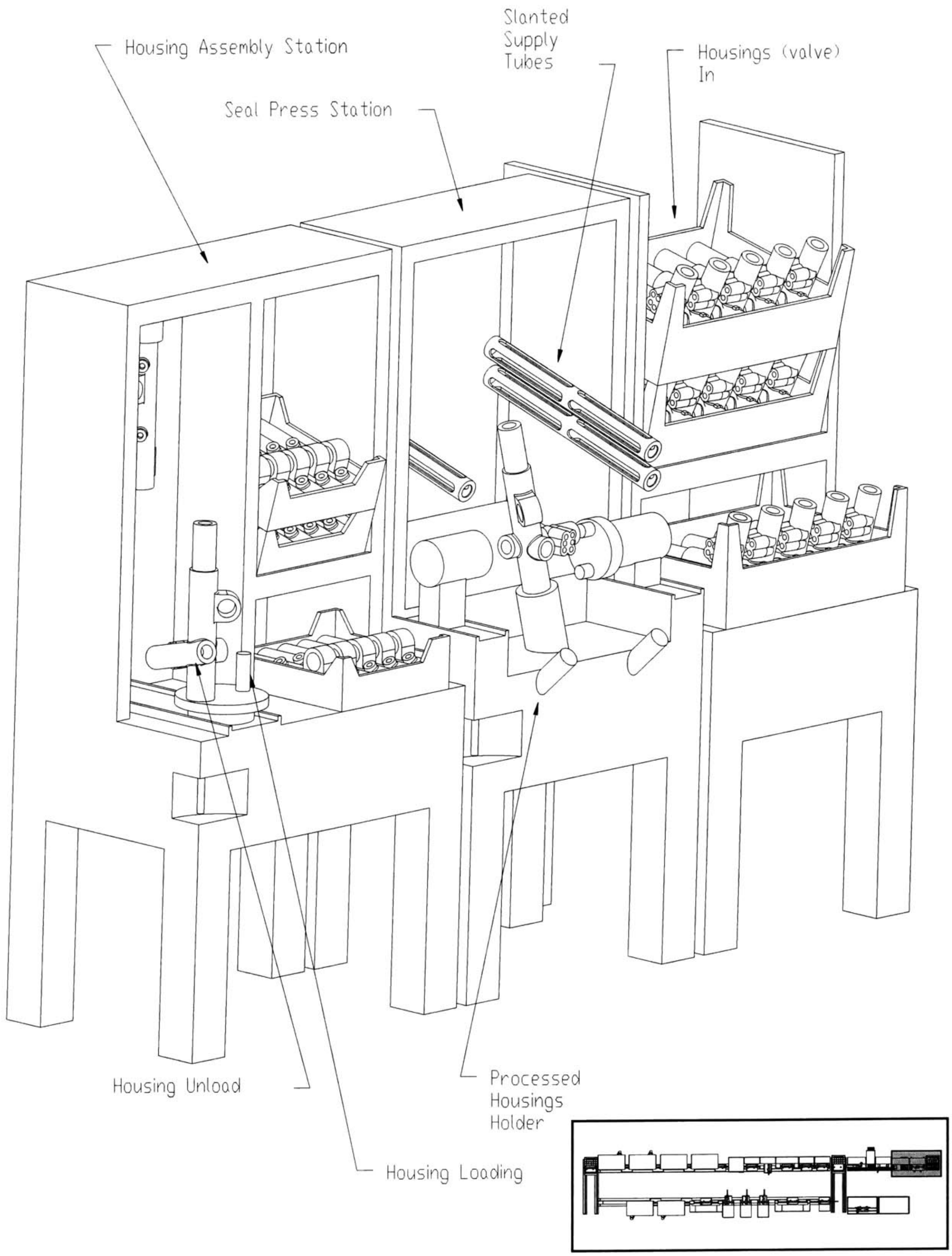


FIGURE 26: Detail View of Stations from the U-222 Assembly Cell

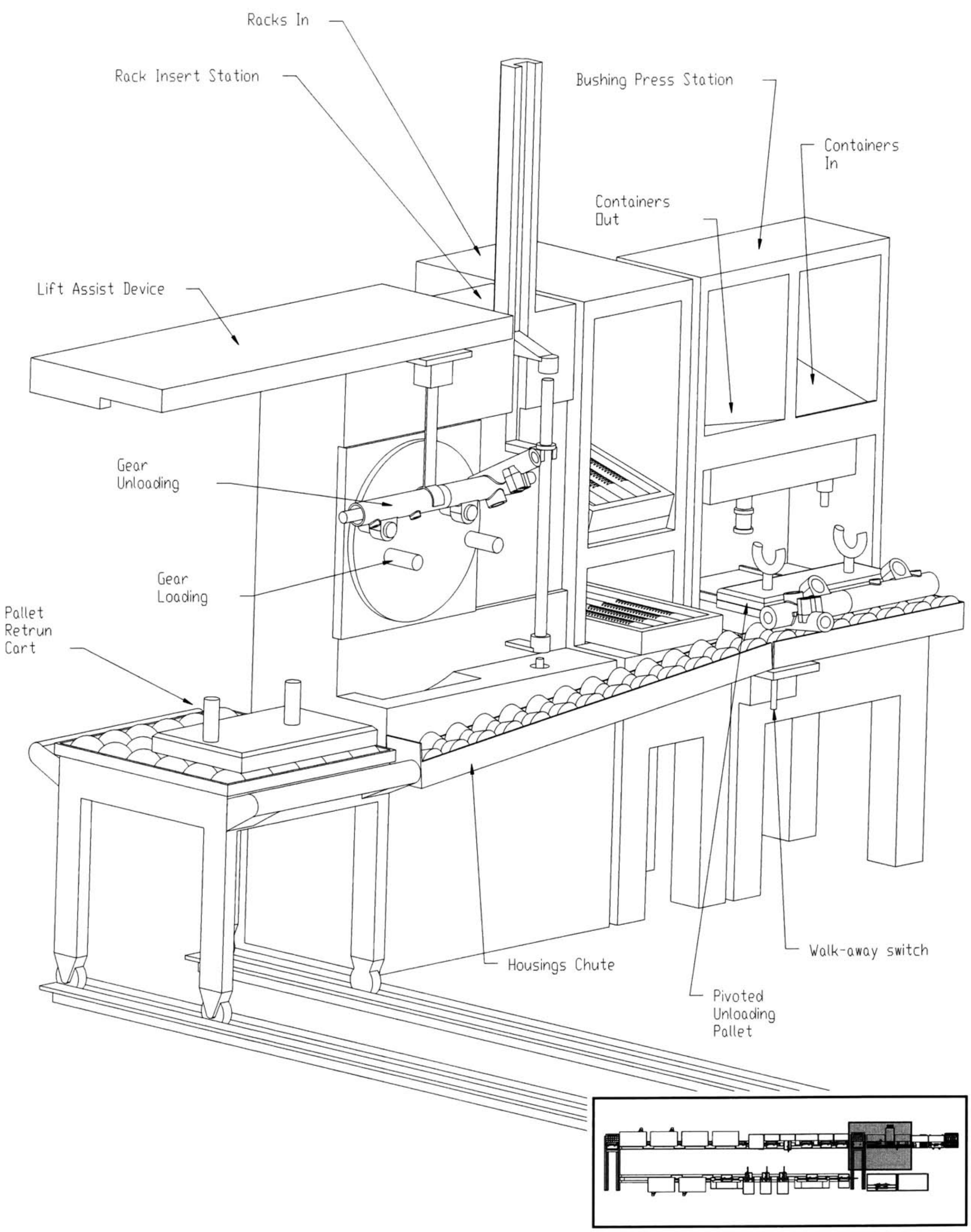


FIGURE 27: Detail View of Stations from the U-222 Assembly Cell

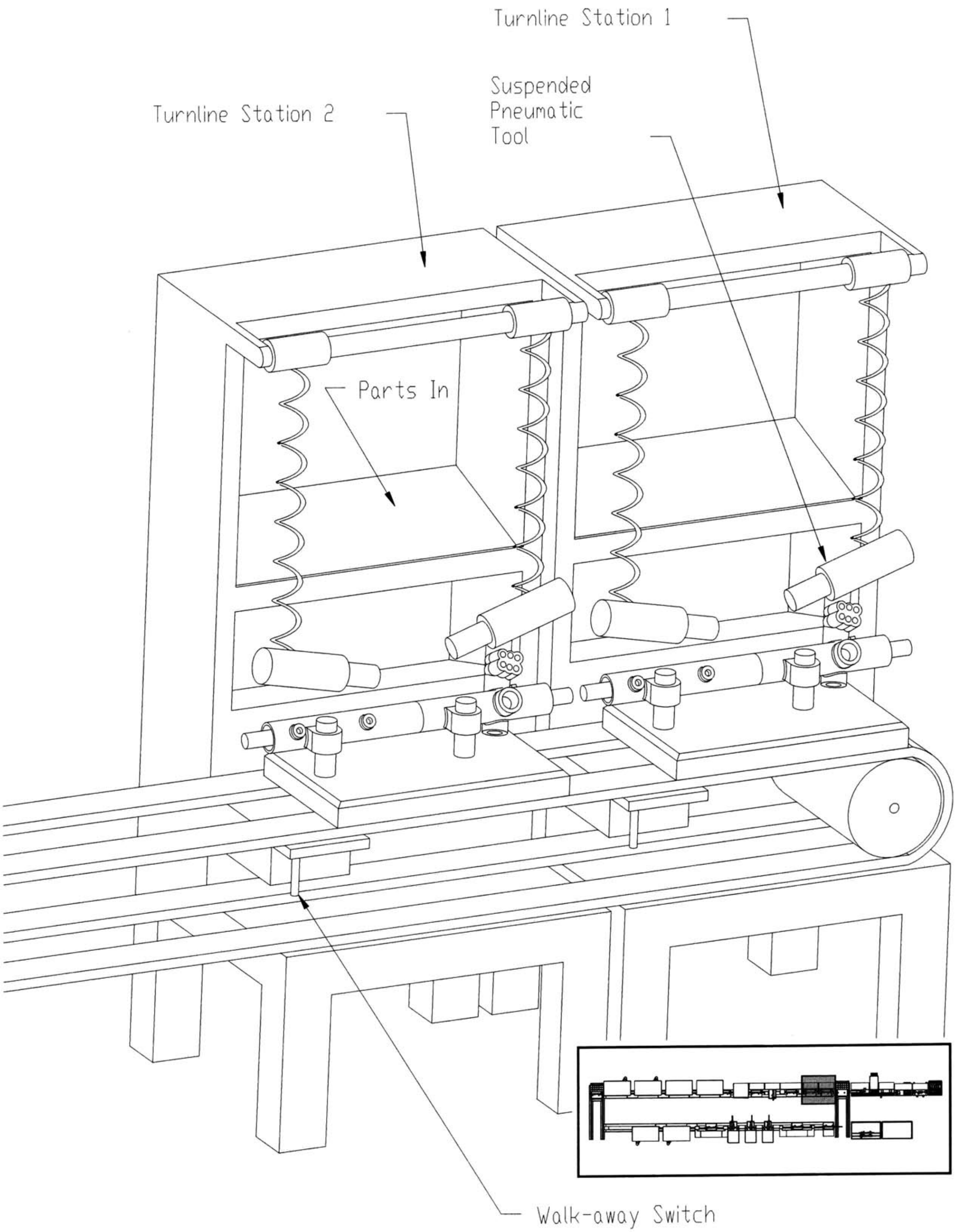


FIGURE 28: Detail View of Stations from the U-222 Assembly Cell

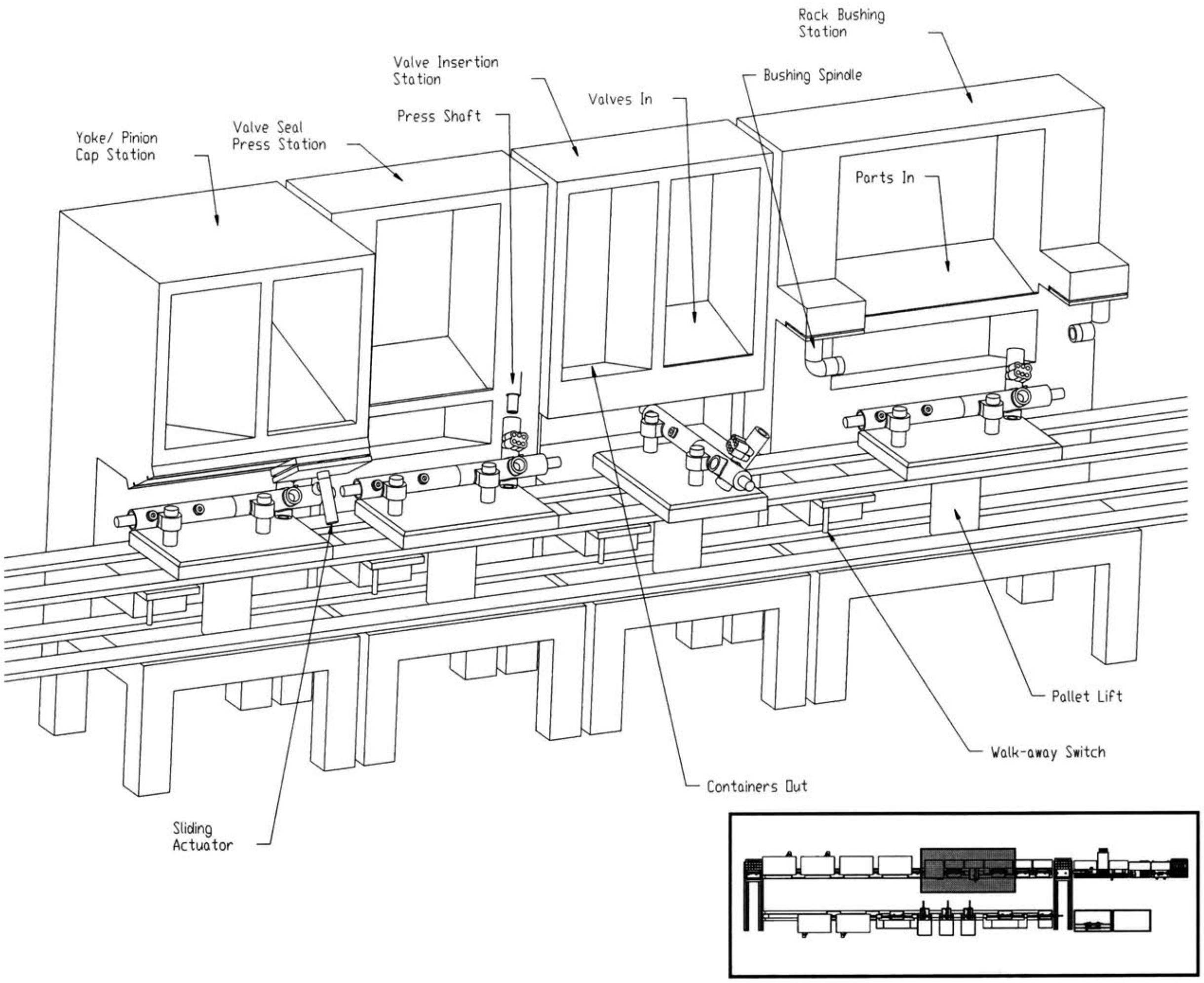
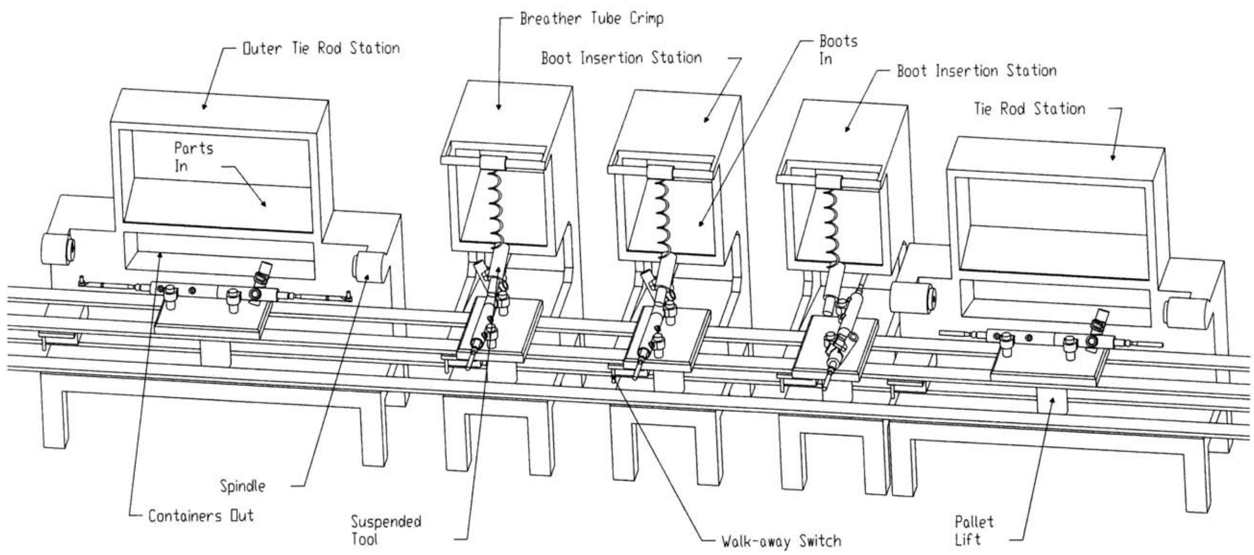


FIGURE 29: Detail View of Stations from the U-222 Assembly Cell



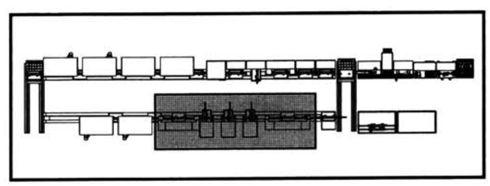


FIGURE 30: Detail View of Stations from the U-222 Assembly Cell

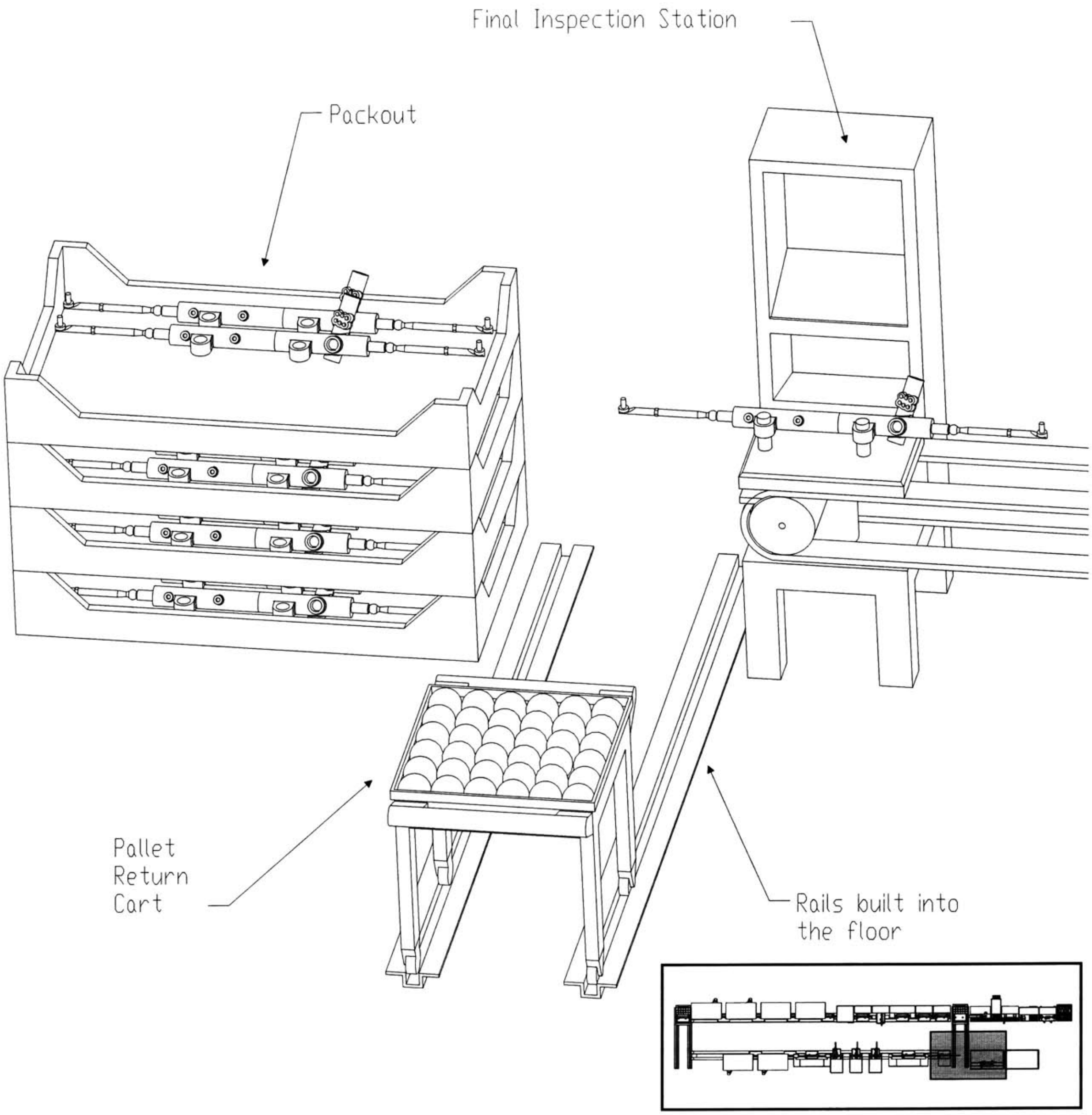


FIGURE 31: Detail View of Stations from the U-222 Assembly Cell

Notice also the attention paid to the design of equipment from the operator's perspective. The component parts needed at each station are presented in the location where they are needed. The loading positions and tools are placed to create a highly ergonomic interface between the equipment and the operator. Also, notice that the larger component parts are delivered in containers of small quantities to reduce walking distance and cell length, to enable standardized material replenishment and to facilitate the changeover from one product type to the next.

PART: U222 Gear (29 second Takt time) **Operators: 11**

PROCESS		TIME (sec)		
#	OPERATION	Man	Walk	Auto
10	Grab housing (valve) from container	3	1	0
20	Unload finished housing from Seal press and place into holder	2	0	0
20	Load housing, load pinion bearing, upper pinion bearing and seal	11	0	0
20	Grab finished housing from holder, hit switch	2	1	10
30	Load housing (valve), grab and load housing (tube)	6	2	0
30	Unload housing assembly, hit switch	3	1	15
40	Load housing assembly, load bushings	10	0	0
40	Slide housing, hit switch	2	1	15
50	Grab rack bar from container	3	1	0
60	Load rack bar, load housing assembly	6	2	0
60	Unload gear and clamp on pallet (auto start rack insert)	7	2	20
70	Start and torque turnline, hit switch	18	2	0
80	Start and torque turnline, hit switch	18	2	0
90	Load rack bushing, hit switch	3	2	15
100	Rotate 90, install valve, Rotate -90, hit switch	20	1	0
110	Load input bearing, seal and snap ring, hit switch	7	1	10
120	Install pinion nut, cap, spring and yoke plug, hit switch	28	0	0
200	Load tie rods & spacer, hit switch	9	2	20
210	Rotate 90, Install boot, clamp and nut (50%)	16	2	0
210	Install boot, clamp and nut (50%), hit switch	12	1	0
220	Rotate 180, Install boot, clamp and nut (50%)	15	1	0
220	Install boot, clamp and nut (50%), hit switch	13	1	0
230	Install breather tube, hit switch	14	1	0
240	Load outer tie rods, hit switch	9	2	20
250	Install res. cap, wipe gear, inspect	10	2	0
250	Unload finished gear, hit switch	3	2	0
	Pack gear into dunnage	8	2	0

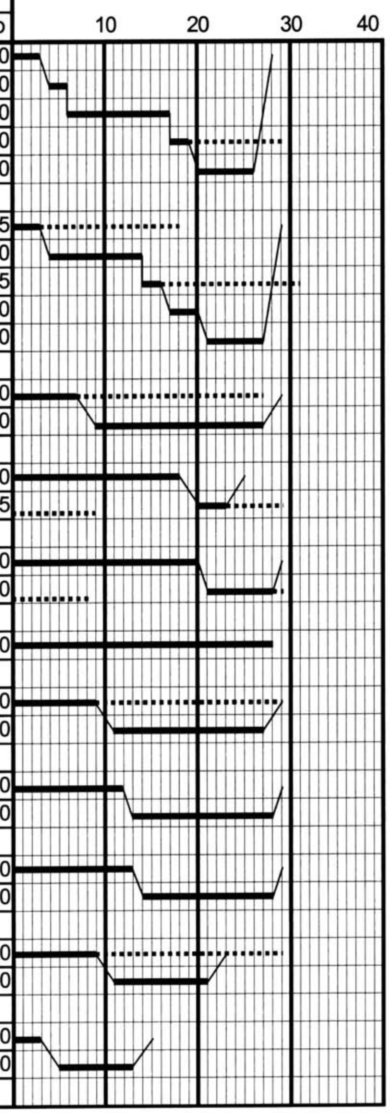


FIGURE 32: Standard Work Combination Chart for the U-222 Assembly Cell

FIGURE 32 shows the standard work diagram for the operation of the U-222 assembly cell. The tasks completed at each station are described under the *Operation* heading, and the number of each operation refers to the station at which the task is completed (refer to FIGURE 33 for the station numbers). Notice that each task is associated with: A *Manual* time that is the actual time the operator takes to complete the task, a *Walk* time that is the time the operator takes to walk to the next operation and a

Automatic time which is the amount of time that the machine takes to complete its cycle once the operator starts it and walks away. FIGURE 33 also shows the work-loops for the 11 operators required to operate the assembly cell.

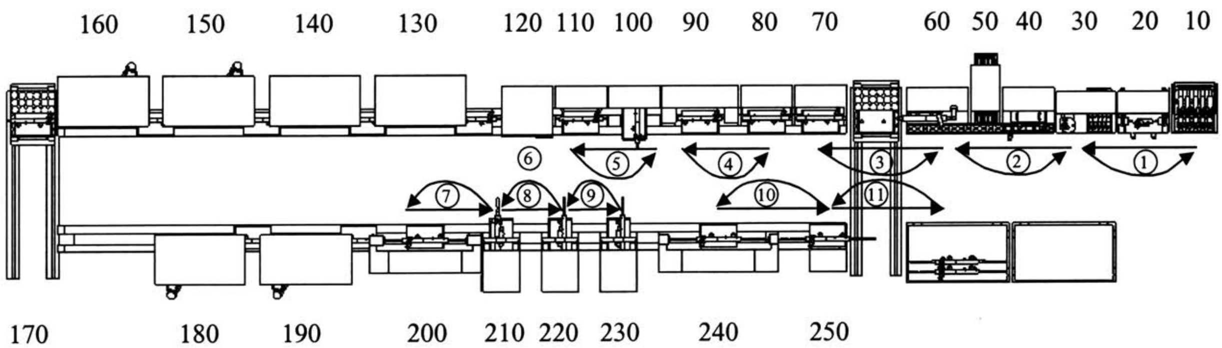


FIGURE 33: U-222 Assembly Cell Work-loops

4.7.- Assessment of the Proposed Assembly System Using the Equipment Evaluation Tool

An evaluation of the U-222 assembly cell using the Equipment Evaluation Tool introduced in Chapter 3 yields the results shown below in FIGURE 34. The average level of achievement across all the FRs being evaluated is 4.8. According to the qualitative evaluation criteria illustrated in FIGURE 12 (page 55), a 4.8 achievement level corresponds to a system characterized by the presence of assembly and/or machining cells that almost adequately implements the FRs of the Toyota Production System and the MSDD. Notice that, once again, the 4.8 was calculated as a straight average of the levels of achievement across all the columns, which gives equal weight to all the FRs from the MSDD that relate to equipment design and that are being evaluated.

Level of Achievement	FR-Q11	FR-Q13	FR-Q123	FR-R11	FR-R12	FR-P121	FR-T22	FR-T32	FR-T5	FR-D11	FR-D2	FR123	FR13
	FRs from Equipment Evaluation Tool												
1													
2													
3	50%	37.5%			25%								
4	50%	37.5%	25%	62.5%	62.5%	12.5%		25%		25%			75%
5		25%	50%	37.5%	12.5%	62.5%		50%	50%		62.5%	100%	25%
6			25%			25%	100%	25%	50%	75%	37.5%		
Sum	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Average Level	3.50	3.88	5.00	4.38	3.88	5.13	6.00	5.00	5.50	5.50	5.38	5.00	4.25
Average Level of Achievement Across All Columns: **4.80**													

FIGURE 34: Assessment of the U-222 Cell Using the Equipment Evaluation Tool

Notice how the scores in the Direct Labor branch (FR-D11 and FR-D2) of the Equipment Evaluation Tool reflect a significant improvement from the WIN 88 line (refer to FIGURE 23) to the U-222 assembly cell. The improvement of the scores reflects the effort placed during the design of the U-222 equipment to achieve the separation of the operator from the machine and realize the benefits listed on page 85, and to design the equipment to provide a highly ergonomic interface between the station and the operator. The high scores in the Delay Reduction branch (FR-T22, FR-T32 and FR-T5) reflect the effort placed to reduce the throughput time of the system, by designing the equipment to operate at takt time, reducing the changeover time, and minimizing systematic operational delays. The compact nature of the design of the U-222 equipment and the reduced floor space it consumes earned it a high score on the Facilities Cost column (FR123), and its flexibility (in terms of volume, different products and ability to reconfigure) earned it high marks on the Production Investment column (FR13).

In comparison with the evaluation of the WIN 88 line (FIGURE 23) the scores in the Equipment Evaluation Tool have improved across the board for the U-222 assembly cell, which is a reflection of the fact that the U-222 equipment was designed from a systems perspective, to satisfy the FRs from the MSDD, which is precisely what the Evaluation Tool measures. Since the U-222 system was designed to perform well on what is being measured by the Equipment Evaluation Tool, then it is expected that it will score high, or at least higher than the WIN 88 system. One of the important topics covered in Prof. David Cochran's dissertation [Cochran, 1994] and his teachings in Production System Design [Cochran, Course 1999], is that systems evolve based on how they are measured, which explains why the WIN 88 system maximizes machine utilization and direct labor costs (deemed as the important metrics for that system) while the U-222 system performs better than the WIN 88 on the Equipment Evaluation Tool. The important point to make is that the Equipment Evaluation Tool is a "better" way to assess the equipment design relative to achieving the system design objectives from the MSDD, and therefore to achieving the high-level enterprise objectives.

Even though the U-222 assembly cell was designed to fulfill the FRs from the MSDD that affect equipment design, it still did not score a perfect rating on the Equipment Evaluation Tool. The reason for the scores that are not quite perfect is twofold. On one hand, many decisions about the design of the U-222 assembly cell are the result of compromises that had to be reached to comply with engineering, safety and investment concerns from the Visteon Indianapolis personnel. For example, in both of the boot stations and in the breather tube stations (Stations 210, 220 and 230 from FIGURE 33, page 93) the steering gear protrudes into the cell, which interferes with the operator movement and inevitable causes wasted motion and prevents the scores in the Direct Labor section (FR-D11 and FR-D2) from being perfect. However, the steering gear is intentionally designed to be in that orientation, because from experience, the Visteon engineers know that is the most comfortable orientation of the gear such that the operator can easily complete the tasks (assemble the boots and breather tube). Also, as mentioned before, the aggregation of demand for this assembly cell forced the cycle time to be 29 seconds, which borders on being too low to enable the separation of the operator from the machines. FIGURE 33 shows how such a low takt time has forced one of the operators to be tied to a station, and it also shows how several stations are shared by more than one operator, which can lead to interference. The lack of full implementation of separation of the operator from the machine (due to the short cycle time) prevents the system from fully achieving the benefits listed on page 85, and forces the scores in the Time Variation section (particularly FR-R11 and FR-R12) and the score in FR-T5 to be less than perfect.

4.8.- Summary

This chapter presented the work done in equipment design to support production system design at Visteon Indianapolis. This case study serves as an example of the application of the equipment design framework outlined in Chapter 2 and also of the Equipment Evaluation Tool introduced in Chapter 3. The project involved concept-level design of equipment for the final assembly of automotive steering gears. The case study centered on the comparison between a high-speed asynchronous line (WIN 88) designed with a traditional mentality of optimizing certain performance metrics, and a proposed assembly cell (U-222) designed to fulfill the FRs from the MSDD relating to equipment design and operation. The comparison was done based on assessments of both systems using the Equipment Evaluation Tool.

The results of the assessment of both the traditional system and the proposed cell using the Equipment Evaluation Tool yielded average achievement levels of 2.26 for the WIN 88 line, and 4.8 for the U-222 cell, out of a maximum of 6. The difference is a reflection of the fact that the U-222 equipment was designed from a systems perspective, to satisfy the FRs from the MSDD that relate to equipment design, which is precisely what the Evaluation Tool measures. This case study helped to illustrate how the U-222 cell can, when compared to the WIN 88 line, better enable the manufacturing system to achieve the enterprise objectives. In addition, it also highlighted the importance of the Equipment Evaluation Tool as an assessment and design tool, since it focuses on measuring how well the equipment design and operation enables the achievement of the FRs from the MSDD that affect equipment design and operation.

Conclusions

This work focused on the design and operation of the equipment in a manufacturing enterprise and on how to make the equipment support the design of the production system. Since the equipment is a critically important element of any production system, it is important to ensure that the design and operation of the equipment enables the production system to achieve its high-level objectives. This thesis introduced a framework and a tool for the design and operation of the equipment so that it supports the design of the production system and the achievement of the enterprise objectives.

Chapter 1 introduced a methodology to design production systems (the PSD framework), which uses Axiomatic Design to identify the thought process and the key decisions that need to be made during the design of all the different elements of a production system, and serves as a method to communicate those decisions to the people in an organization. Using Axiomatic Design for the design of production systems leads to designs that are simple, easy to operate and that achieve business objectives. The PSD framework encapsulates the knowledge from the Toyota Production System literature and experience in such a way that a system designed using the PSD framework will achieve the principles of *lean production*.

Chapter 2 presented a summary of the equipment design framework developed by Arinez and Cochran to design equipment that meets the system requirements identified by the PSD framework. The subset of FRs and DPs from the MSDD that affect the design of equipment was identified, and that subset served as the basis for a framework for the design of equipment that achieves the requirements of the system. A twofold framework was presented. The first method consists in using the subset of FRs/DPs from the MSDD that affect equipment design to elaborate guidelines to be supplied to the equipment designers, which include specific information on the mechanical, electrical and other relevant physical properties that the equipment must have to achieve the system requirements. The second method involves the direct application of Axiomatic Design methodology to the design of equipment by developing an Equipment Design Decomposition (EDD), which is linked to the MSDD to ensure that the EDD provides a detailed description of the physical properties of the equipment that are needed to achieve the system requirements.

Chapter 3 presented an Equipment Evaluation Tool that can be used to assess how well the design and operation of a particular piece (or set) of equipment within a manufacturing enterprise supports the design of the production system. It uses the subset of FRs from the MSDD that affect the design of equipment to identify which physical characteristics the equipment should have to satisfy these requirements. The Equipment Evaluation Tool can be very valuable to a manufacturing enterprise since it serves to measure how well the current design and operation of equipment supports the production system design. The tool can also be very useful in providing a guideline or set of objectives for the improvement of current equipment or the design of new equipment.

Finally, Chapter 4 discussed a case study of the application of the equipment design framework and the Equipment Evaluation Tool. The case study centered on a project for the concept-level design of equipment for the final assembly of automotive steering gears. The case study illustrated how equipment designed using the equipment design framework and the Equipment Evaluation Tool can, when compared to equipment designed in a traditional fashion, better enable manufacturing enterprises to achieve their high-level objectives. In addition, it also highlighted the importance of the Equipment Evaluation Tool as an assessment and design tool, since it focuses on measuring how well the equipment design and operation enables the achievement of the FRs from the MSDD that affect equipment design and operation.

References

Arinez, Jorge. An Equipment Design Approach to Achieve Manufacturing System Requirements. Ph.D. Dissertation, Massachusetts Institute of Technology, 2000.

Arinez, Jorge F. and David S. Cochran. "Application of a Production System Design Framework to Equipment Design." Proceedings of the 32nd CIRP International Seminar on Manufacturing Systems. Leuven, Belgium, May 24-26, 1999.

Arinez, Jorge F., Micah T. Collins, David S. Cochran, Melissa D. Uhl and Paul Cook. "Design of an Automotive Compressor Production System Using Lean Manufacturing Design Guidelines." Proceedings of the 1999 SAE International Automotive Manufacturing Conference. 99IAM-34. Detroit, MI, May 11-13, 1999.

Black, J. T. The Design of the Factory with a Future. New York: McGraw Hill, 1991.

Bröte, Staffan, David S. Cochran, Ania Mierzejewska, Brandon Carrus, Steve Rupp and Jeff Smith. "Integrating the Production Information System with Manufacturing Cell Design – A Lean, Linked Cell Production System Design Implementation." Proceedings of the 1999 SAE International Automotive Manufacturing Conference. 99IAM-28. Detroit, MI, May 11-13, 1999.

Carrus, Brandon J. and David S. Cochran. "Application of a Design Methodology for Production Systems." Annals of the 2nd International Conference on Engineering Design and Automation. Maui, HI, July 1998.

Charles, Michael D., David S. Cochran and Daniel C. Dobbs. "Design of Manufacturing Systems to Support Volume Flexibility." Proceedings of the 1999 SAE International Automotive Manufacturing Conference. 99IAM-27. Detroit, MI, May 11-13, 1999.

Chu, Alex K. and David S. Cochran. "Measuring Manufacturing System Design Effectiveness Based on the Manufacturing System Design Decomposition." Proceedings of the Third World Congress on Intelligent Manufacturing Processes and Systems. Cambridge, MA, June 28-30, 2000.

Cochran, David S. The Design and Control of Manufacturing Systems. Ph.D. Dissertation, Auburn University, 1994.

---. Lean Production System Design. A Hands-On Course for the Design and Implementation of a Lean Production System. Handout package from training course. Framingham, MA, January 20-22, 1999.

---. "The Production System Design and Deployment Framework." Proceedings of the 1999 SAE International Automotive Manufacturing Conference. Detroit, MI, May 11-13, 1999.

Cochran, David S. and Daniel C. Dobbs. "Mass vs. Lean Plant Design Evaluation Using the Production System Design Decomposition." Transactions of NAMRI/SME. Volume XXVIII, Paper No. 00-063-MS. Lexington, KY, May 24-26, 2000.

Cochran, David S., Yong-Suk Kim and Jongyoon Kim. "The Alignment of Performance Measurement with the Manufacturing System Design." Proceedings of the First International Conference on Axiomatic Design. Cambridge, MA, June 21-23, 2000.

Duda, James W., David S. Cochran, Jose Castañeda-Vega, Mike Baur, Ron Anger and Shahram Taj. "Application of a Lean Cellular Design Decomposition to Automotive Component Manufacturing System Design." Proceedings of the 1999 SAE International Automotive Manufacturing Conference. 99IAM-26. Detroit, MI, May 11-13, 1999.

Gomez, Deny D., Daniel C. Dobbs and David S. Cochran. "Equipment Evaluation Tool Based on the Manufacturing System Design Decomposition." Proceedings of the Third World Congress on Intelligent Manufacturing Processes and Systems. Cambridge, MA, June 28-30, 2000.

Monden, Yasuhiro. Toyota Production System: An Integrated Approach to Just In Time. 2nd ed. Norcross, Georgia: Industrial Engineering and Management Press, 1993.

Ohno, Taiichi. Toyota Production System. Beyond Large-Scale Production. Portland, OR: Productivity Press, 1988.

Parnaby, J. "Concept of a Manufacturing System." International Journal of Production Research. Vol. 17-2 (1979): 123-135

Production System Design Laboratory, MIT. Manufacturing System Design Decomposition v5.1 with Performance Metrics. Internal Document, 2000.

Shingo, Shigeo. A Study of the Toyota Production System From an Industrial Engineering Viewpoint. Trans. Andrew P. Dillon. Portland, OR: Productivity Press, 1989

Suh, Nam P. The Principles of Design. New York: Oxford University Press, 1990.

Suh, Nam P., David S. Cochran and Paulo C. Lima. "Manufacturing System Design." Annals of 48th General Assembly of CIRP. Vol. 47-2 (1998): 627-639.

Visteon Indianapolis Plant. DEW-98 / X-200 Left Hand Drive Rack & Pinion Steering Gear Assembly. Internal Document, 1999.

Wang, Andrew. Design and Analysis of Production Systems in Aircraft Assembly. M.S. Thesis, Dept. of Mechanical Engineering, Massachusetts Institute of Technology, 1999.

Womack, James P. and Daniel T. Jones. Lean Thinking: Banish Waste and Create Wealth in your Organization. New York: Simon and Schuster, 1996.

Womack, James P., Daniel T. Jones and Daniel Roos. The Machine that Changed the World. New York: Harper Perennial, 1991.

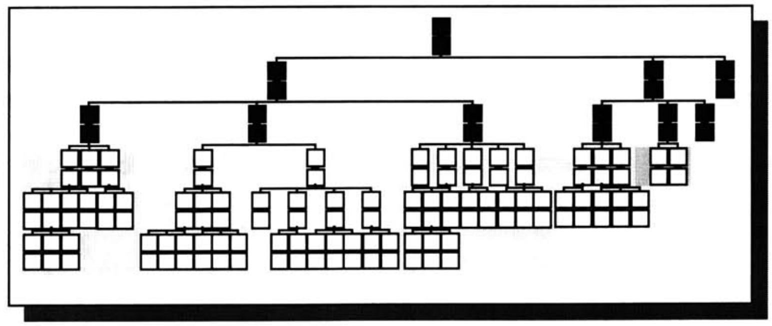
Appendix A: Manufacturing System Design Decomposition v5.1

Level I

FR1
Maximize long-term return on Investment

PM1
Return on investment over system lifecycle

DP1
Manufacturing System Design



Level II

FR11
Maximize sales revenue

PM11
Sales revenue

DP11
Production to maximize customer satisfaction

FR12
Minimize manufacturing costs

PM12
Manufacturing costs

DP12
Elimination of non-value adding sources of cost

FR13
Minimize investment over production system lifecycle

PM13
Investment over system lifecycle

DP13
Investment based on a long term strategy

Level III

FR111
Manufacture products to target design specifications

PM111
Process capability

DP-111
Production processes with minimal variation from the target

FR112
Deliver products on time

PM112
Percentage on-time deliveries

DP112
Throughput time variation reduction

FR113
Meet customer expected lead time

PM113
Difference bet. throughput time and customer's expect. lead time

DP113
Mean throughput time reduction

FR121
Reduce waste in direct labor

PM121
Percentage of operators' time spent on wasted motions and waiting

DP121
Elimination of non-value adding manual tasks

FR122
Reduce waste in indirect labor

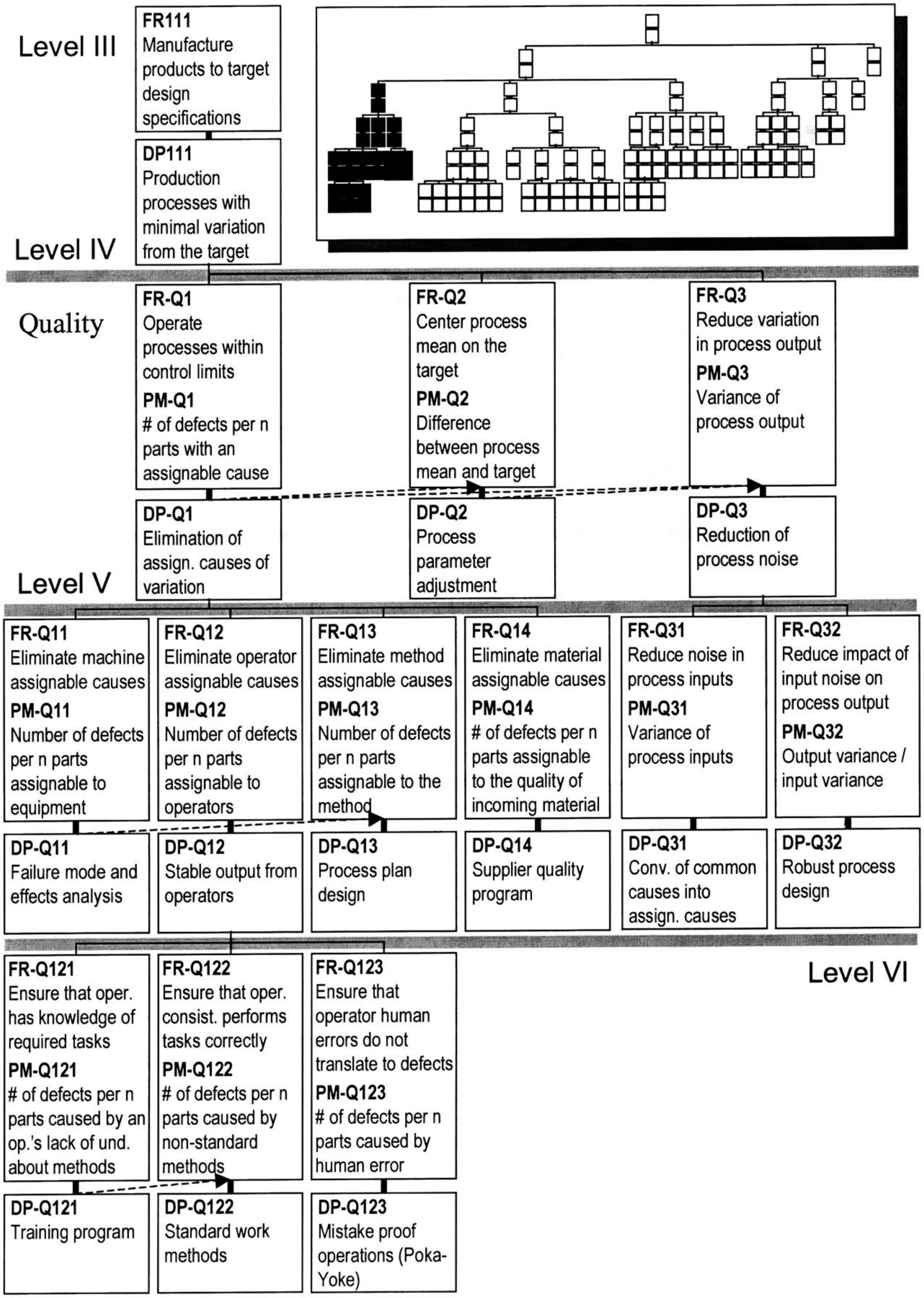
PM122
Amount of required indirect labor

DP122
Reduction of indirect labor tasks

FR123
Minimize facilities cost

PM123
Facilities cost

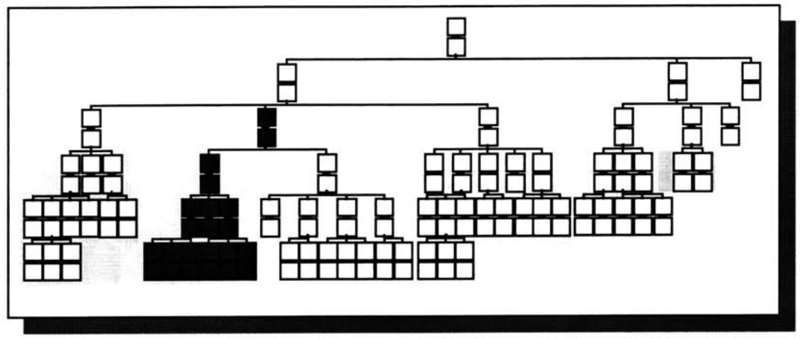
DP123
Reduction of consumed floor space


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

DP-R11
Subsystem config. to enable op.'s detection of disr.

FR-R12
Comm. problems to the right people
PM-R12
Time between id. of what the disrup. is & support res. understanding it

DP-R12
Process for feedback of operation's state

FR-R13
Solve problems immediately
PM-R13
Time bet. support res. understanding what the disr. is & problem resolution

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

DP-R111
Increased operat. sampling rate of equipment status

FR-R112
Identify disrupt. where they occur
PM-R112
Time between id. of disruption and id. of where the disruption occurred

DP-R112
Simplified material flow paths

FR-R113
Identify what the disruption is
PM-R113
Time between id. of where disrupt. occurred and id. of what the disruption is

DP-R113
Context sensitive feedback

FR-R121
Identify correct support resources
PM-R121
Time between id. of what the disruption is and id. of the correct support resource

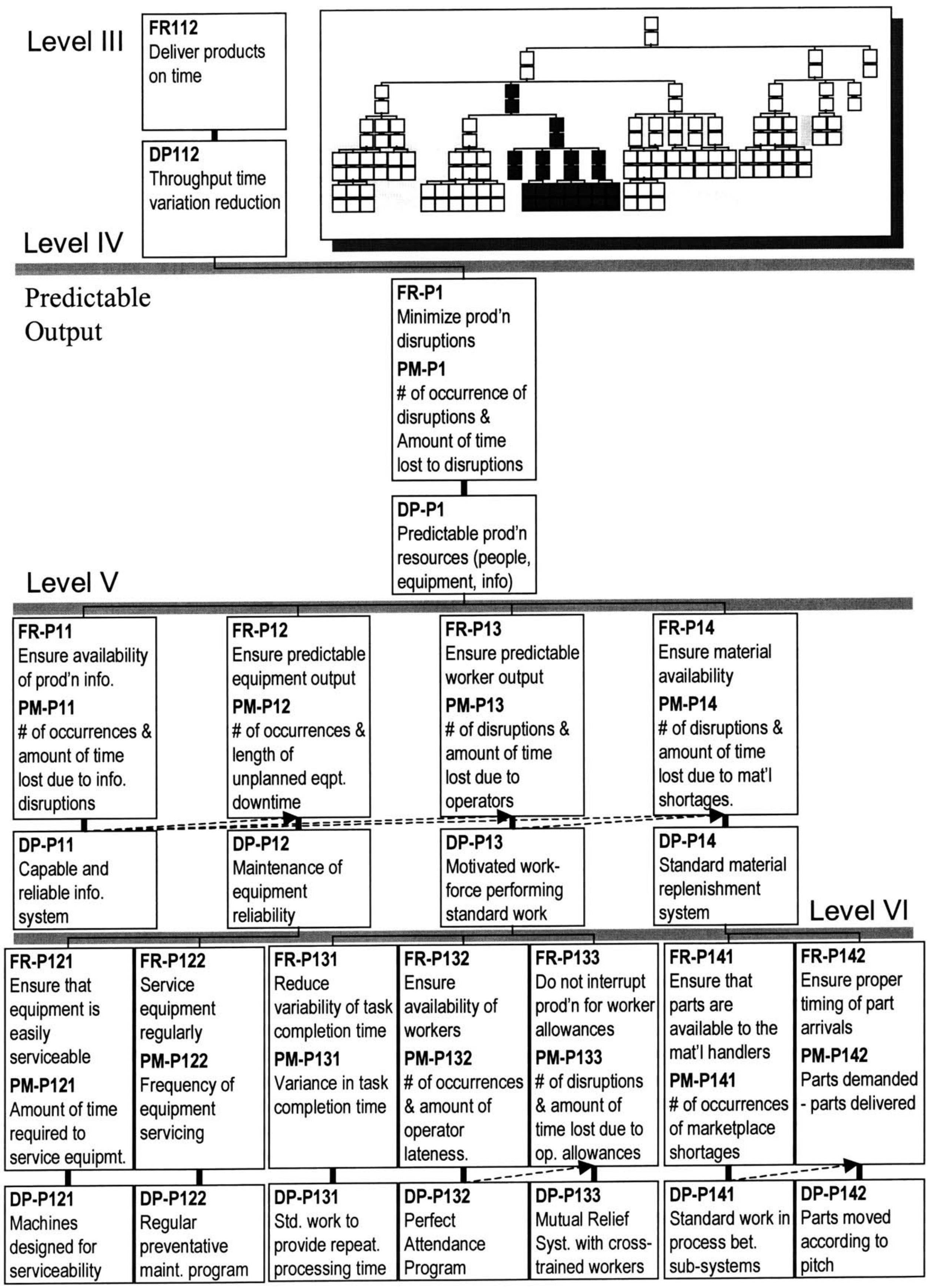
DP-R121
Specified support resources for each failure mode

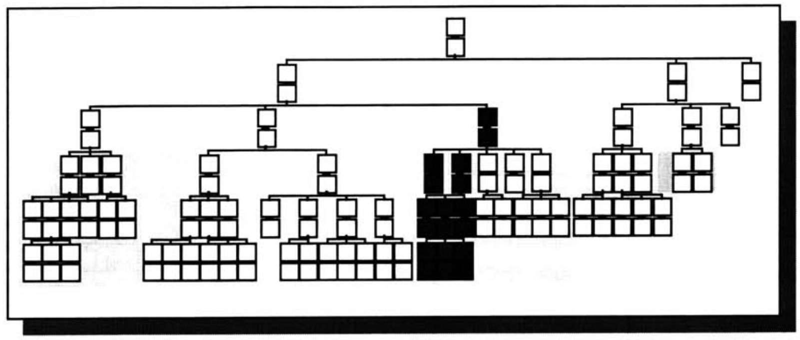
FR-R122
Minimize delay in contacting correct support resources
PM-R122
Time between identification and contact of correct support resource

DP-R122
Rapid support contact procedure

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-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

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

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

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)

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

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

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

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

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)

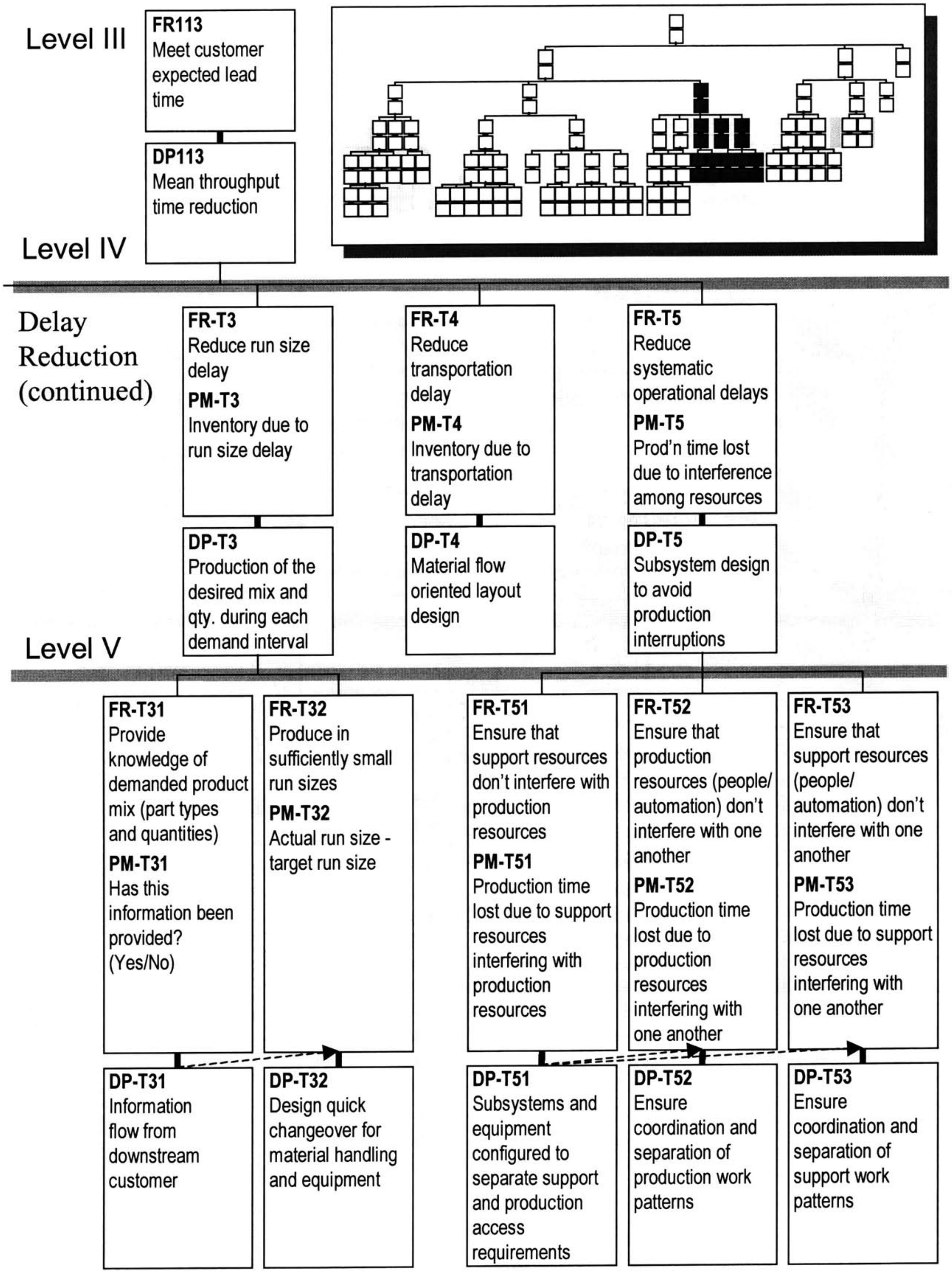
DP- T221
Design of approp. auto. work content at each station

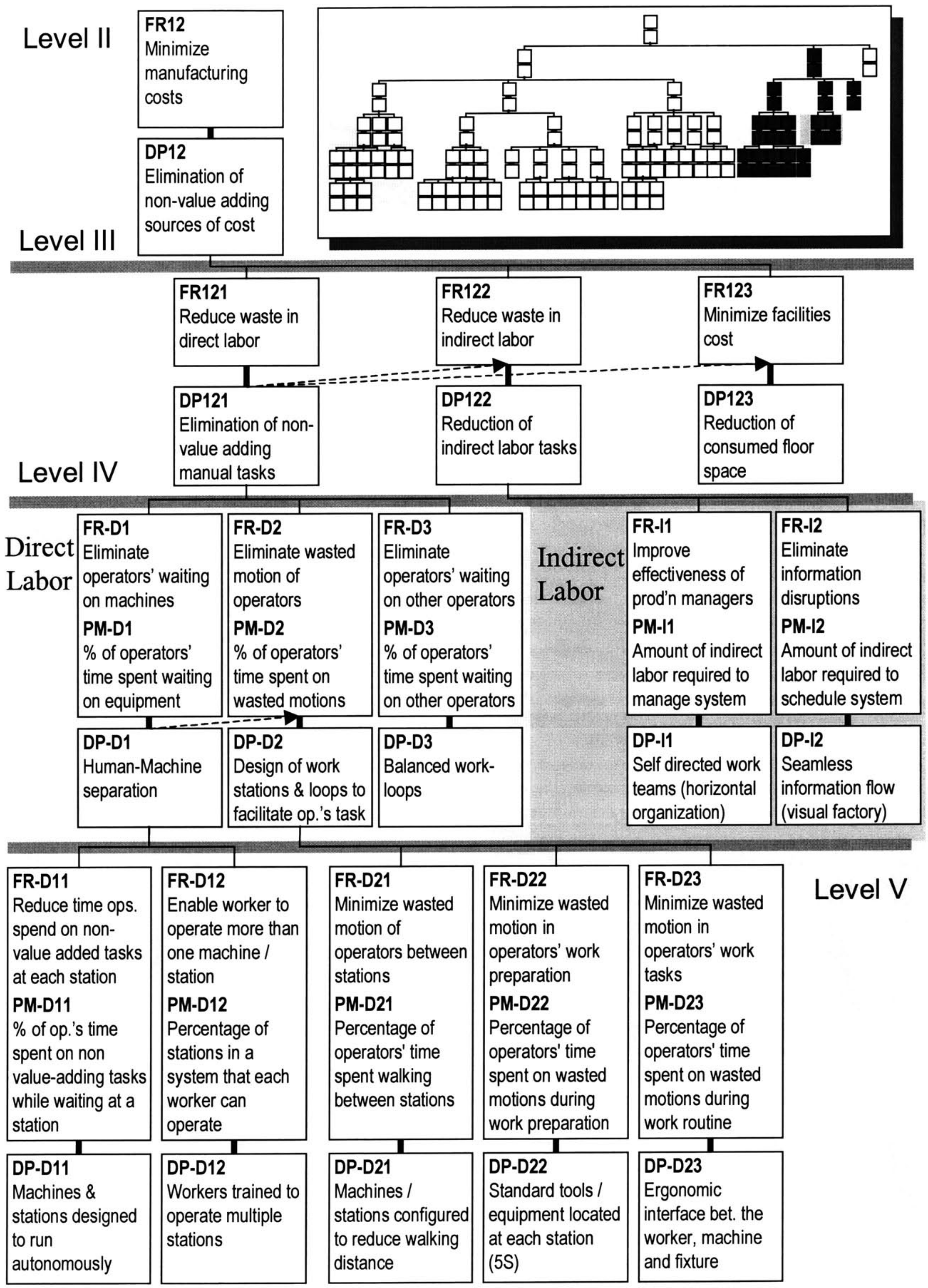
FR-T222
Ensure that manual cycle time ≤takt time
PM-T222
Has this been achieved? (Yes / No)

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

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

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)
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
Level V
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