The Development and Application of the Manufacturing System Design Evaluation Tool and Performance Measurement Based on the Manufacturing System Design Decomposition

by

Alex K. Chu

B.S. Mechanical Engineering
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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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Abstract

Manufacturing systems are evaluated based on performance measurements which have largely been developed in management cost accounting systems and other financial measures of success. Using these financial metrics to evaluate the operational performance of a manufacturing system can lead to behavior which contradicts the ultimate goals of a manufacturing system. In order to reinforce the goals of a manufacturing system, the performance measurements must be aligned with the system design.

Therefore, performance measurements have been developed, based on the Manufacturing System Design Decomposition, which are aligned with the functional requirements, or goals, of a manufacturing system design. These performance metrics support the goals of a manufacturing system design and promote operational behavior which corresponds to these goals.

Furthermore, a Manufacturing System Design (MSD) Evaluation Tool has been developed, based on the Manufacturing System Design Decomposition, to assess the effectiveness of a manufacturing system design. This tool evaluates the design of a manufacturing system, instead of measuring the operational performance of a manufacturing system. By determining the effectiveness of a manufacturing system design, the weakest areas of a design can be pinpointed. Improvements can be made to a manufacturing system design, which will lead to improvements in the operational performance of a manufacturing system.

Using the performance measurements and MSD Evaluation Tool together can result in a superior manufacturing system design because the goals of the manufacturing system design are continuously reinforced both during the design and operation of the manufacturing system.

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

Acknowledgements

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I would also like to thank the students, graduate and undergraduate, of the Production System Design laboratory in the Laboratory for Manufacturing and Productivity at MIT. Many of them provided invaluable assistance in the formation of this thesis. I would particularly like to thank the students involved in the projects at Coclisa, Indianapolis, Monroe, and Sterling for their assistance with the Applications chapter of this thesis. Thanks go to David Estrada, Deny Gomez, Dan Dobbs, Ania Mierzejewska, Brandon Carrus, and Jim Duda.

Finally, I would like to thank my family for their support. I would like to thank my parents for their ongoing guidance as I pursue my goals and dreams. Also, I would like to thank my brother, Maurice, for his support and insight during these years.

- Alex K. Chu

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Chapter 1: Introduction

1.1 Introduction

This thesis discusses the development and application of the Manufacturing System Design (MSD) Evaluation Tool and Performance Measurements (PMs). Both the MSD Evaluation Tool and PMs have been developed based on the Manufacturing System Design (MSD) Decomposition.

The MSD Evaluation Tool measures the effectiveness of a manufacturing system design rather than the performance of a manufacturing system in operation. By using the Evaluation Tool to assess a manufacturing system design, the effectiveness of specific areas of a system design can be determined. The tool evaluates sixteen separate areas of a manufacturing system design on a scale of six possible levels of achievement. Level 1 corresponds to a very poor system design, and Level 6 corresponds to a very good system design. Not only does the Evaluation Tool indicate the design effectiveness of a current manufacturing system, but the tool also provides insight about which areas of a manufacturing system design need the most improvement efforts.

The Performance Measurements measure the performance of a manufacturing system in operation. The most important aspect of the PMs is that they must be aligned with the functional requirements of a manufacturing system design. Performance measurements which are not aligned with the requirements of a system design may affect the system's performance adversely. The performance metrics may, in fact, support behavior which contradicts the functional requirements of a manufacturing system design. Therefore, key performance measurements have been developed based on the MSD Decomposition. These key PMs are completely aligned with the functional requirements of a manufacturing system design, and they support and promote the achievement of the manufacturing system design objectives.

1.1.1 Outline

Chapter 2 briefly introduces the Axiomatic Design (AD) methodology, which is the foundation for the Manufacturing System Design Decomposition. The development and decomposition of functional requirements (FRs) and design parameters (DPs) is discussed. In addition, the two axioms of Axiomatic Design are presented and explained: Independence Axiom and Information Axiom. Finally, an example is given to illustrate Axiomatic Design.

Chapter 3 introduces the Manufacturing System Design (MSD) Decomposition. The overall structure of the MSD Decomposition is presented. First, the high level FR-DP pairs are discussed. Then, the six branches of the MSD Decomposition are discussed with some examples: Quality, Identifying and Resolving Problems, Predictable Output, Delay Reduction, Direct Labor, and Indirect Labor. Finally, the Production System Design (PSD) Framework is introduced and discussed. The PSD Framework consists of the MSD Decomposition, MSD Matrix, MSD Implementation Flowchart, MSD Evaluation Tool, Equipment Evaluation Tool, and MSD Deployment Steps.

Chapter 4 discusses the development of the Performance Measurements (PMs) based on the MSD Decomposition. The PM for each functional requirement (FR) of the MSD Decomposition is explained in detail. In addition, a few key performance metrics are identified for the high-level FRs and for each branch of the MSD Decomposition.

Chapter 5 discusses the development of the Manufacturing System Design (MSD) Evaluation Tool based on the MSD Decomposition. The derivation of the evaluation criteria is explained, and the six levels of achievement for a manufacturing system design are explained with examples. Also, a qualitative scoring method is developed and discussed. Finally, each column of the MSD Evaluation Tool is illustrated in great detail.

Chapter 6 applies both the MSD Evaluation Tool and the key Performance Measurements developed in chapters 4 and 5 to several different projects. These projects include automotive component manufacturing plants in Coclisa, Indianapolis, Monroe, and Sterling. The MSD Evaluation Tool was used to assess the manufacturing system design both before the project was begun and after the project was completed. In addition, the key performance measurements were applied to the manufacturing system both before and after the projects as well. Using both the MSD Evaluation Tool and key Performance Measurements to evaluate these projects served to validate the tools, and the results showed the degree of success and improvement for each project over the existing manufacturing system.

Chapter 2: Axiomatic Design

2.1 *Introduction to Axiomatic Design*

Axiomatic Design (AD) is a design methodology which attempts to provide a science base for design [Suh, 1990]. Traditionally, design has not been viewed as a scientific process. It has been considered a skill which is innate to some, not a skill which can be developed. Axiomatic Design provides a structured method to relate requirements and solutions for a design problem.

2.2 *Mapping from Functional Requirements to Design Parameters*

The first important step in Axiomatic Design is to understand the customer requirements. The objectives or strategy of the enterprise must be aligned with meeting and/or exceeding the defined customer requirements. These customer requirements must be translated into functional requirements (FRs) which will guide the design.

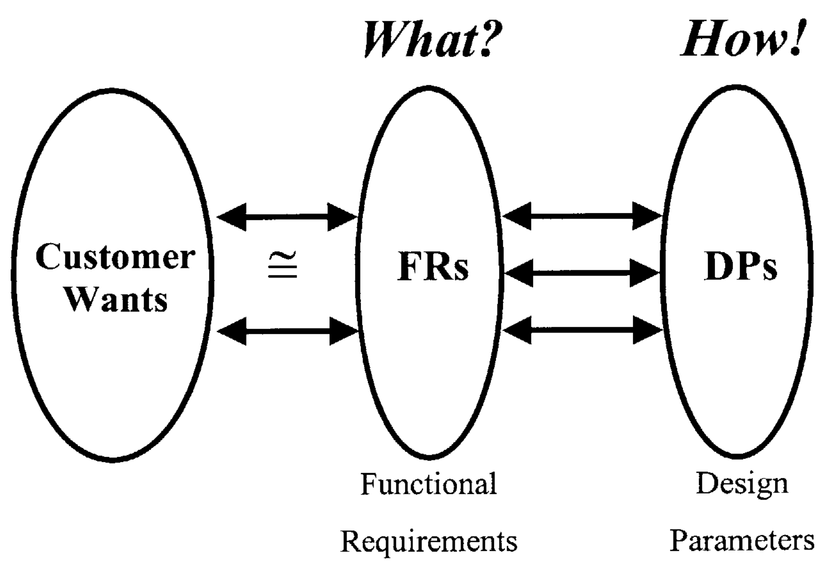


Figure 2.1: Mapping FRs to DPs in Axiomatic Design

The functional requirements identify *what* needs to be achieved by the design in order to meet the customer requirements. The FRs are then mapped to their corresponding design parameters (DPs), as shown in Figure 2.1. The DPs identify *how* the FRs will be satisfied and usually relate to actual characteristics of the design.

For example, one customer requirement for a design may be portability. From this one customer requirement, several functional requirements may be derived. One of these functional requirements might be creating a lightweight design. Then, the design parameter would incorporate some target value for the weight of the design. This mapping process seeks to ensure that a design adheres to the requirements set forth by the customers.

2.3 Decomposition of a Design

Following the mapping process from each functional requirement to its corresponding design parameter, the DP is decomposed into lower level FRs if the DP needs to be further defined. These lower level FRs state *what* needs to be done in order to accomplish the parent DP. Then, similarly, the lower level FRs are mapped to their corresponding DPs. This decomposition process shown in Figure 2.2 continues until the design is complete.

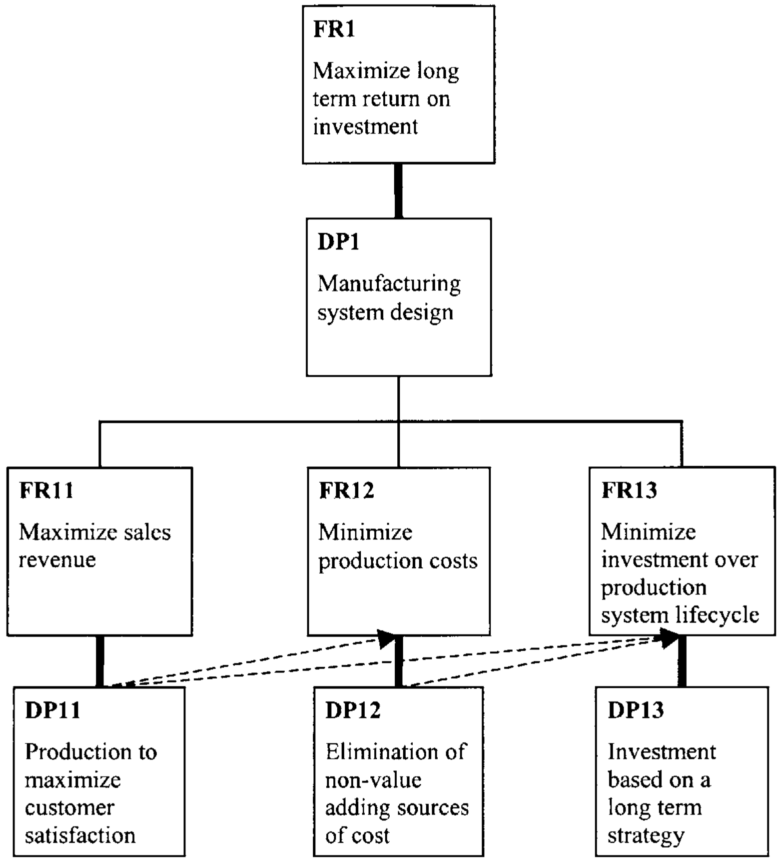


Figure 2.2: Decomposition and Mapping Process

2.4 Independence Axiom and Information Axiom

During the decomposition process, there are two axioms in Axiomatic Design which govern the development of an excellent design: the Independence Axiom, and the Information Axiom.

Independence Axiom: Maintain the independence of FRs.
Information Axiom: Minimize the information content of the design.

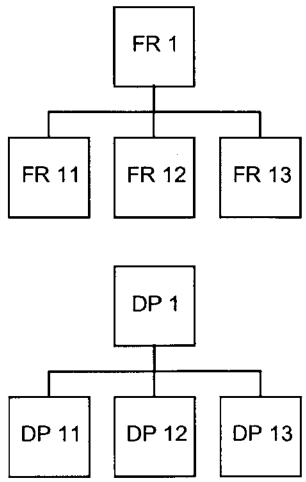
The Independence Axiom asserts that excellent designs should maintain the independence of the FRs. Each DP should influence one and only one FR in order to maintain complete independence. When a DP affects more than one FR, this condition creates some degree of coupling. Several DPs may influence a single FR and as a result, may create the need for optimization and evaluation of tradeoffs in order to best satisfy all the functional requirements of a design.

The Information Axiom asserts that good designs should have minimum information content. This means that designs which have the highest probability of satisfying the requirements are better. This probability is inversely related to the amount of information required to fulfill the requirements. Therefore, the Information Axiom seeks to minimize the amount of complexity in a design in terms of the information required and the relative difficulty of creating or implementing the design.

Excellent designs are uncoupled, path-independent, and simple. This is shown by the Design Matrix in the upper third of Figure 2.3. Notice that each DP affects only its corresponding FR, making the matrix diagonal. This is the best possible design.

Good designs are decoupled, path-dependent, and moderately complex. This is shown by the Design Matrix in the middle third of Figure 2.3. Notice that some DPs affect more than one FR; however, the matrix can be made triangular. This is still an acceptable design.

Poor designs are coupled and complicated. This is shown by the Design Matrix in the lower third of Figure 2.3. Notice that some DPs affect each others' FRs, which prevents the matrix from being made triangular. This design is unacceptable from an Axiomatic Design standpoint because it violates the Independence Axiom.



$$\begin{array}{cc} & \begin{array}{ccc} \text{DP 11} & \text{DP 12} & \text{DP 13} \end{array} \\ \begin{array}{c} \text{FR 11} \\ \text{FR 12} \\ \text{FR 13} \end{array} & \begin{pmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{pmatrix} \end{array}$$

Best - Uncoupled

$$\begin{array}{cc} & \begin{array}{ccc} \text{DP 11} & \text{DP 12} & \text{DP 13} \end{array} \\ \begin{array}{c} \text{FR 11} \\ \text{FR 12} \\ \text{FR 13} \end{array} & \begin{pmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{pmatrix} \end{array}$$

Acceptable - Decoupled

$$\begin{array}{cc} & \begin{array}{ccc} \text{DP 11} & \text{DP 12} & \text{DP 13} \end{array} \\ \begin{array}{c} \text{FR 11} \\ \text{FR 12} \\ \text{FR 13} \end{array} & \begin{pmatrix} X & X & X \\ X & X & X \\ X & X & X \end{pmatrix} \end{array}$$

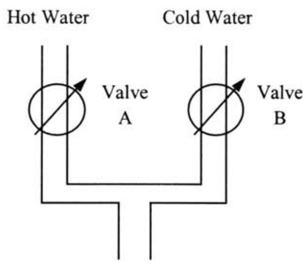
Poor - Coupled

Figure 2.3: Differences Among Designs using Axiomatic Design

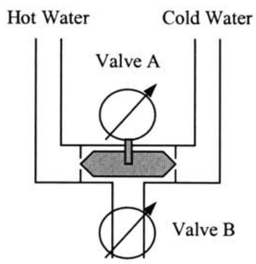
2.5 Axiomatic Design: Water Faucet Example

In order to illustrate the two axioms, the classic water faucet example is presented in Figure 2.4 [Swenson and Nordlund, 1996]. The functional requirements (FRs) of a water faucet are controlling the water temperature and flowrate. The upper half of the figure shows a water faucet with a hot water valve and a cold water valve, the two design parameters (DPs) designated for the two FRs. The Design Matrix shows that this is a poor, coupled design since both DPs affect both FRs. Turning valve A affects both the temperature and the flowrate of the water, as does turning valve B. Therefore, this design is unacceptable from an Axiomatic Design perspective.

The lower half of the figure shows a water faucet with a water temperature valve and a flowrate valve, the two new DPs designated for the two FRs. The Design Matrix shows that this is an excellent, uncoupled design since each DP affects only one FR. In this case, each DP has been specifically chosen to satisfy only its corresponding FR, and they control water temperature and flowrate independently of each other. This is an excellent design from an Axiomatic Design viewpoint.



	DP 1: Valve A	DP 2: Valve B
FR 1: Control Water Temperature	X	X
FR 2: Control Water Flow	X	X



	DP 1: Valve A	DP 2: Valve B
FR 1: Control Water Temperature	X	O
FR 2: Control Water Flow	O	X

X = The DP affects the FR,
O = The DP does not affect the FR

Figure 2.4: Water Faucet Example for Axiomatic Design

Furthermore, in order to decrease the information content of this design, the two valves can be integrated into a single mechanism. For example, horizontal movement can be used to control temperature, and vertical movement can be used to control flowrate. Physical integration while maintaining functional independence is one method to decrease information content. Water faucets which use this design along with an integrated control mechanism are now becoming fairly commonplace.

Chapter 3: Manufacturing System Design Decomposition

3.1 Introduction to the Manufacturing System Design Decomposition

The Manufacturing System Design Decomposition (MSDD) has been developed based on the Axiomatic Design (AD) methodology [Suh, 1990]. The MSDD decomposes a general system design for discrete parts manufacturing. There are six levels of FR-DP pairs in the Decomposition shown in Figure 3.1 [Cochran et. al., 1999]. The first level functional requirement is very broad and encompassing, "Maximize long-term return on investment," and the sixth level functional requirements are specific details of a manufacturing system design, such as "Ensure that automatic cycle time ≤ minimum takt time."

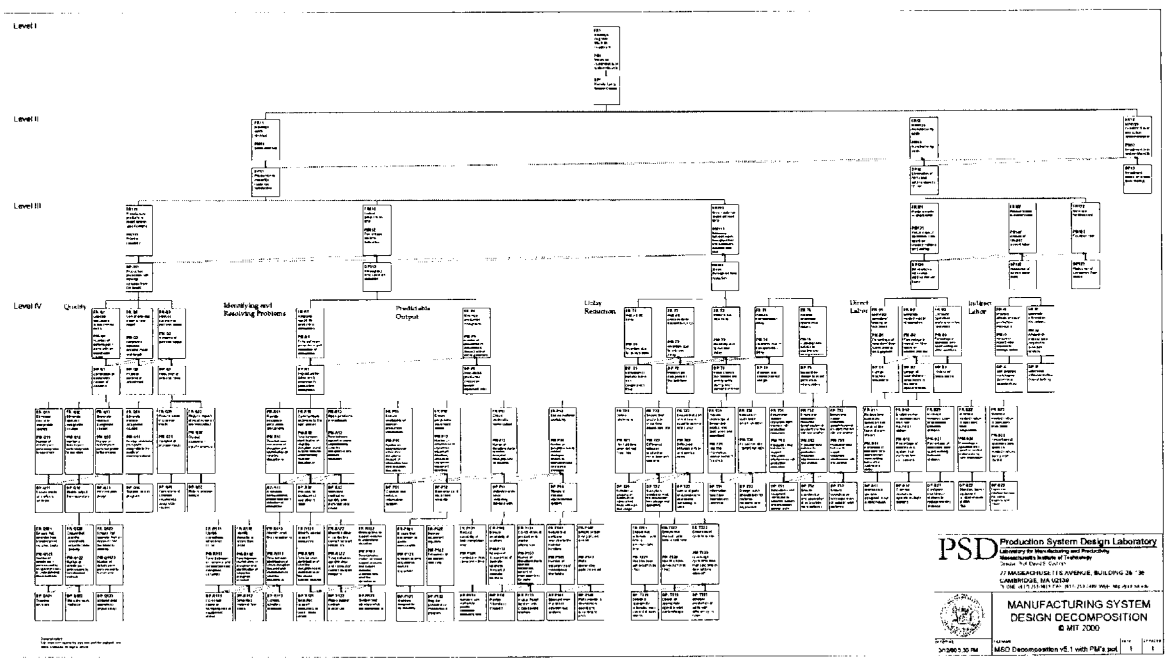


Figure 3.1: Manufacturing System Design Decomposition

3.2 High Level Objectives of the MSDD

The Manufacturing System Design Decomposition decomposes a single FR "Maximize long-term return on investment" which states the highest level objective of manufacturing within an enterprise. The second level FRs of the MSDD seek to maximize sales revenue, minimize production costs, and minimize investment over the production system lifecycle. The third level FRs further decompose the design into manufacture products to target design specifications, deliver products on time, meet the customer expected lead time, reduce waste in direct labor, reduce waste in indirect labor, and minimize facilities cost. The top three levels of the MSDD are considered the high level objectives of the system design, and they are shown here in Figure 3.2.

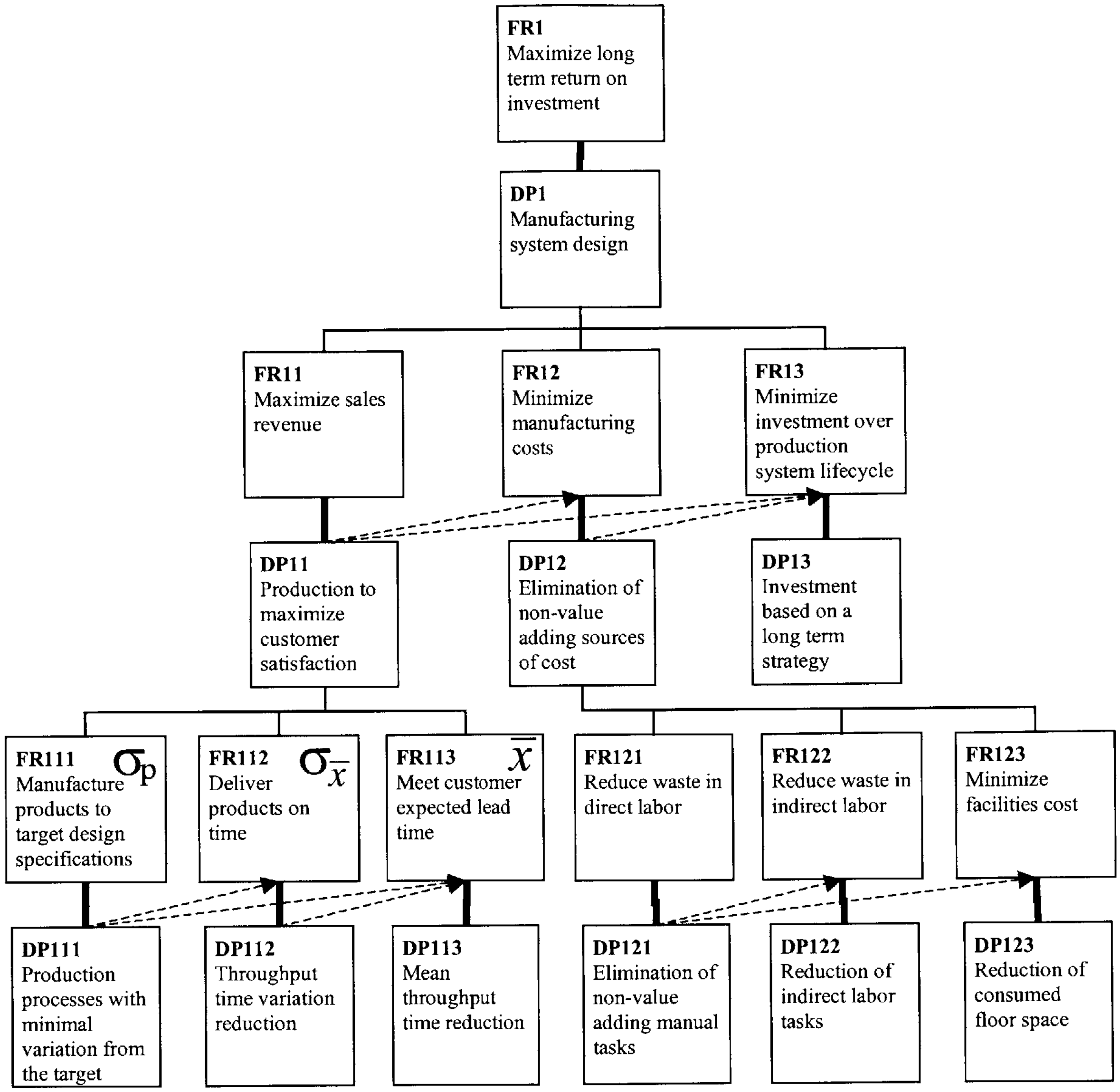


Figure 3.2: High Level Objectives of the MSDD

3.3 Lower Level Objectives of the MSDD

The lower level objectives (levels 4 through 6) of the MSDD are divided into six branches, or categories: Quality, Identifying and Resolving Problems, Predictable Output, Delay Reduction, Direct Labor, and Indirect Labor. These six branches are illustrated in Figure 3.3, and they are briefly described below [Kuest, 1999].

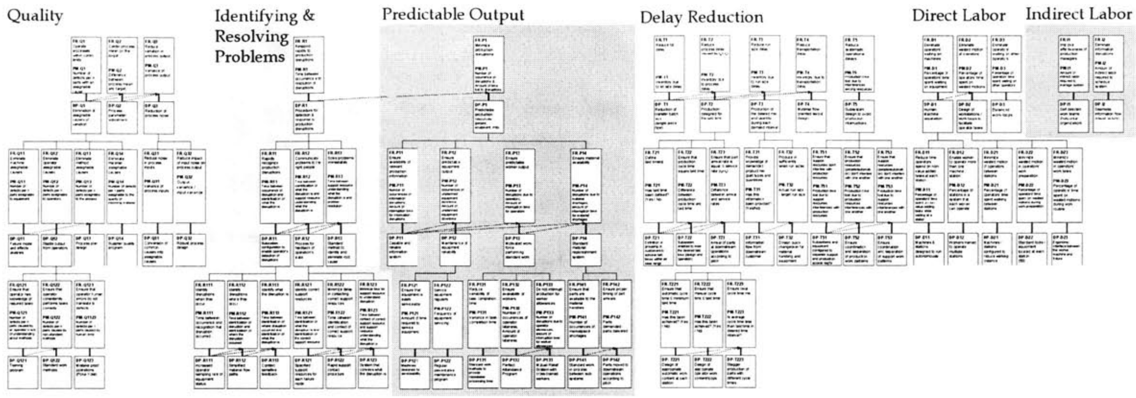


Figure 3.3: Six Branches of the MSDD

3.3.1 Quality Branch

The Quality branch of the Manufacturing System Design Decomposition shown in Figure 3.4 decomposes the following FR-DP pair:

FR 111: Manufacture products to target design specifications

DP 111: Production processes with minimal variation from the mean

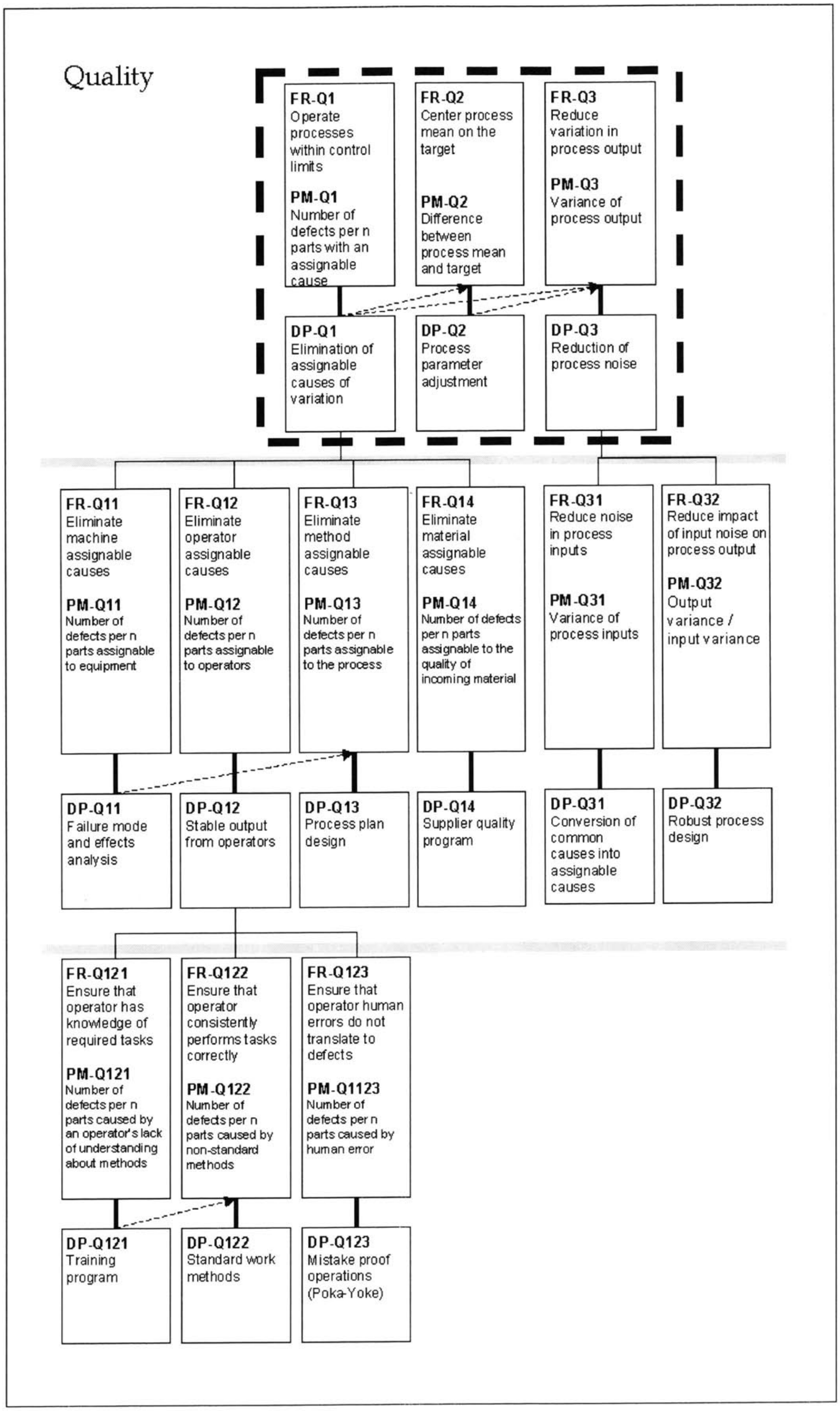
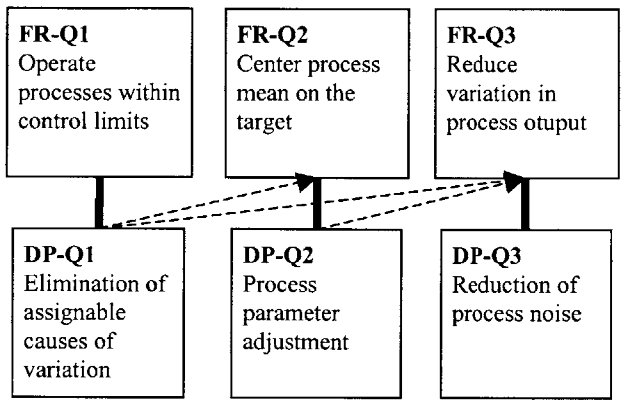


Figure 3.4: Quality Branch of the MSDD

In order to accomplish DP 111, processes must be stable, be centered on the target mean, and have little variation. The examples which follow illustrate the top level FR-DP pairs of the Quality branch, specifically FRs-Q1, Q2, and Q3 which are shown in Figure 3.5 along with the design matrix.



$$\begin{Bmatrix} FR\text{-}Q1 \\ FR\text{-}Q2 \\ FR\text{-}Q3 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP\text{-}Q1 \\ DP\text{-}Q2 \\ DP\text{-}Q3 \end{Bmatrix}$$

Figure 3.5: Top Level of the Quality Branch with the Design Matrix

Figure 3.6 shows examples of statistical process control charts for processes with different characteristics [Montgomery, 1985]. The first SPC chart portrays an unstable process which does not remain within the acceptable control limits. The second SPC chart depicts a stable process which remains within the control limits but is not centered on the target mean. The third SPC chart illustrates a stable process which is centered on the target mean but still has very large variation from the mean. Finally, the fourth SPC chart represents a stable process which is centered on the mean and has reduced variation. This stable process has eliminated all types of assignable causes of variation (machine, operator, method, and material) as well random causes of variation. When all these causes of variation have been eliminated, the processes will be able to produce with minimal variation from the mean. This branch is further decomposed into more specific functional requirements and design parameters which will create stable, centered, and minimally variable processes.

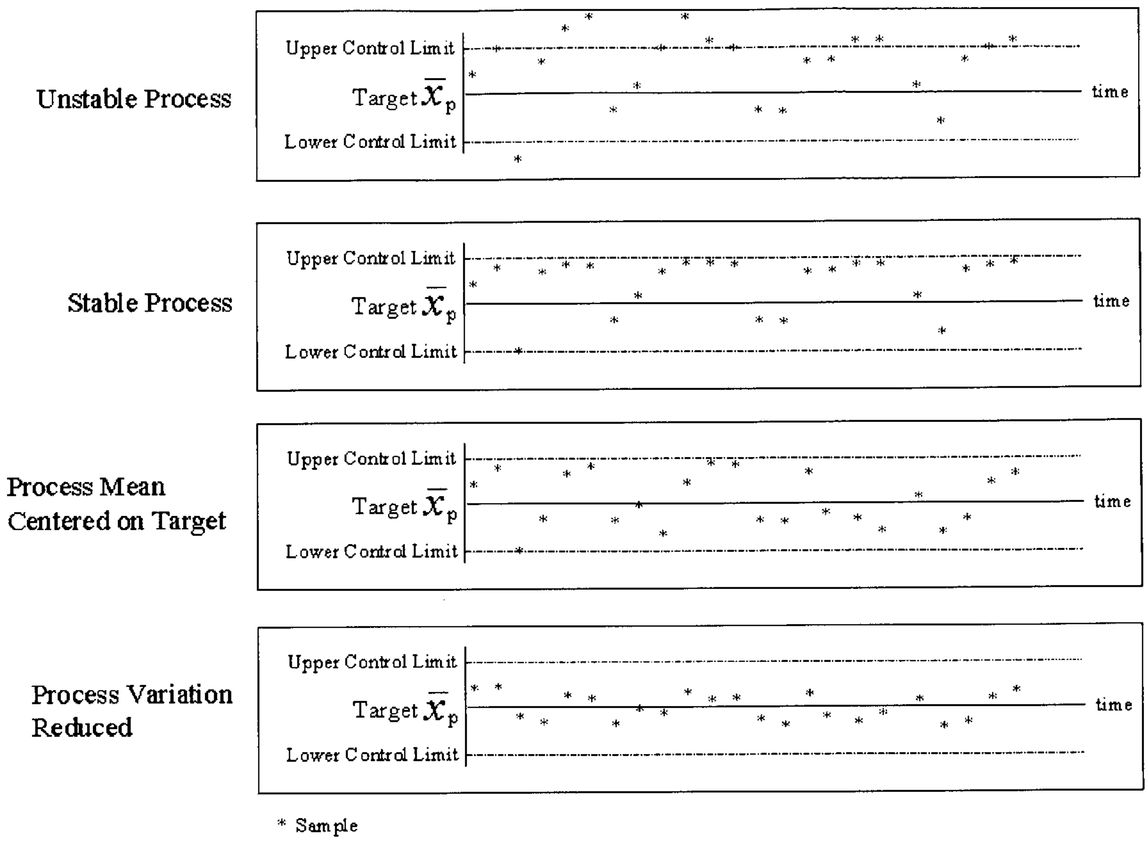


Figure 3.6: Statistical Process Control Charts Showing Processes with Different Characteristics

3.3.2 Identifying and Resolving Problems Branch

The Identifying and Resolving Problems branch of the Manufacturing System Design Decomposition shown in Figure 3.7 decomposes the following FR-DP pair:

FR-R1: Respond rapidly to production disruptions

DP-R1: Procedure for detection and response to production disruptions

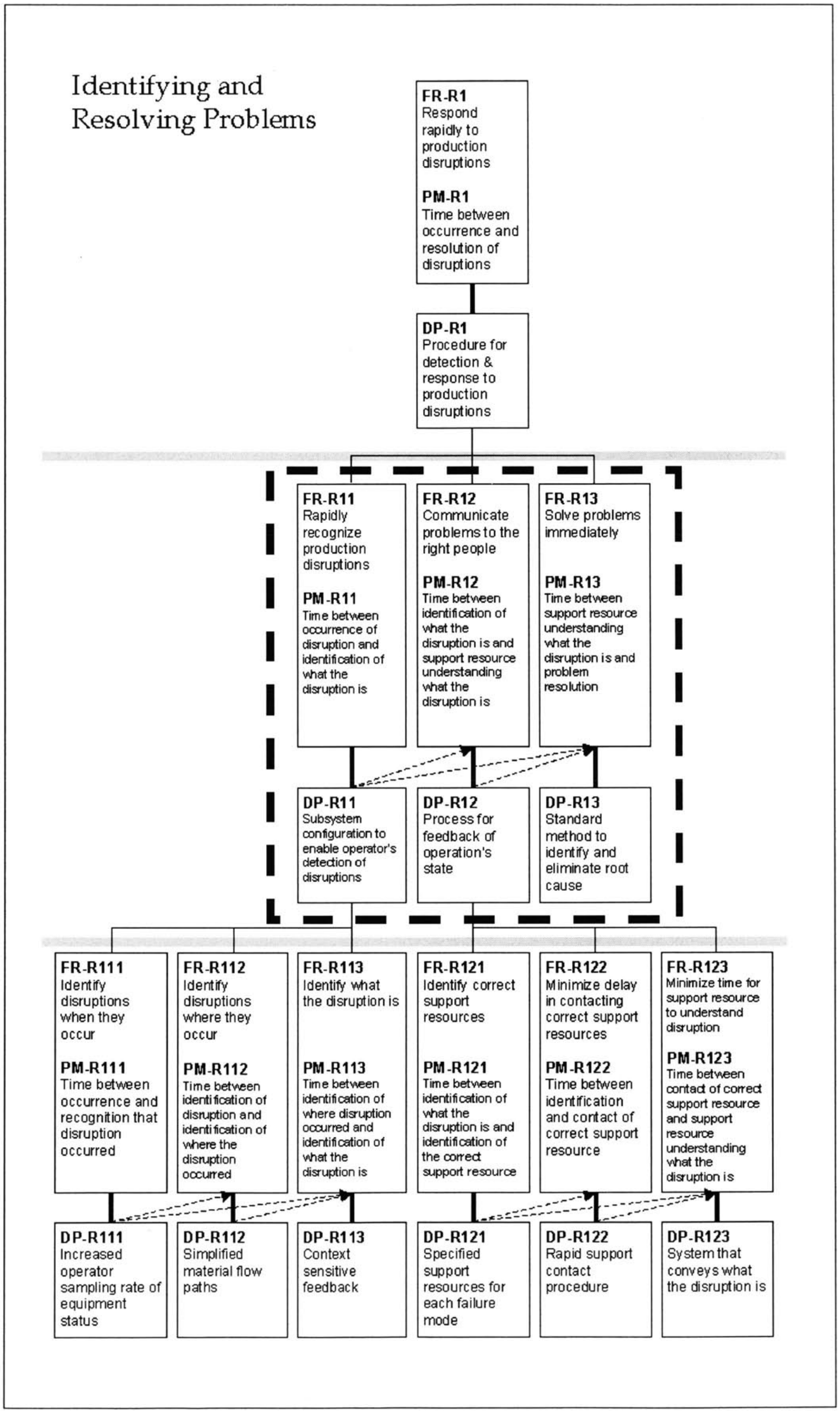
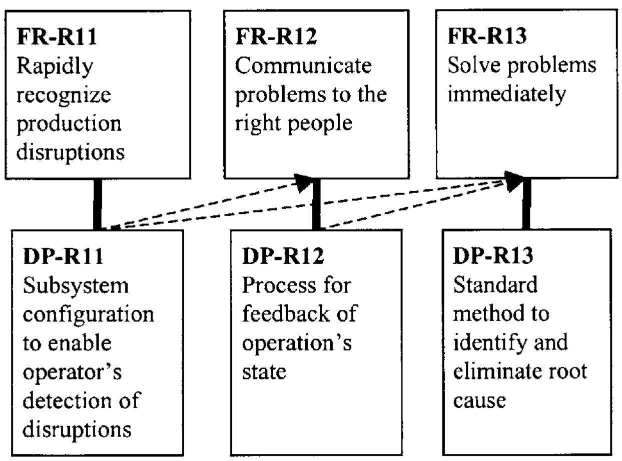


Figure 3.7: Identifying and Resolving Problems Branch of the MSDD

In order to accomplish DP-R1, disruptions must be recognized quickly, communicated to the right people, and resolved immediately. Recognition includes identifying disruptions when and where they occur, and recognizing the type of disruptions. Communication involves identifying and contacting the correct support resources, and providing sufficient information about the disruptions. The example which follows is divided into three sections corresponding to the middle level FR-DP pairs of the Identifying and Resolving Problems branch, specifically FRs-R11, R12, and R13 which are shown in Figure 3.8 along with the design matrix.



$$\begin{Bmatrix} FR\text{-}R11 \\ FR\text{-}R12 \\ FR\text{-}R13 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP\text{-}R11 \\ DP\text{-}R12 \\ DP\text{-}R13 \end{Bmatrix}$$

Figure 3.8: Middle Level of the Identifying and Resolving Problems Branch with the Design Matrix

Figure 3.9 graphically illustrates a timeline starting from the occurrence of a production disruption to the final resolution of the disruption. When these steps are taken to identify and respond to production disruptions quickly, the variation in the throughput time of the system will also be reduced, which corresponds to the upper level DP 112: Throughput time variation reduction.

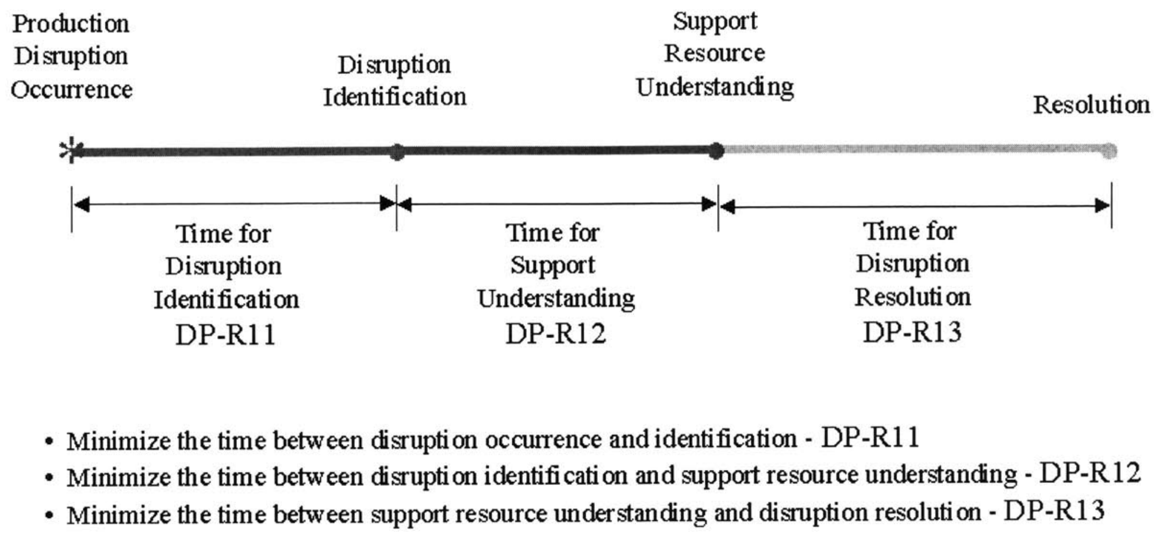


Figure 3.9: Timeline Showing the Procedure for Resolving a Production Disruption

3.3.3 Predictable Output Branch

The Predictable Output branch of the Manufacturing System Design Decomposition shown in Figure 3.10 decomposes the following FR-DP pair:

FR-P1: Minimize production disruptions

DP-P1: Predictable production resources

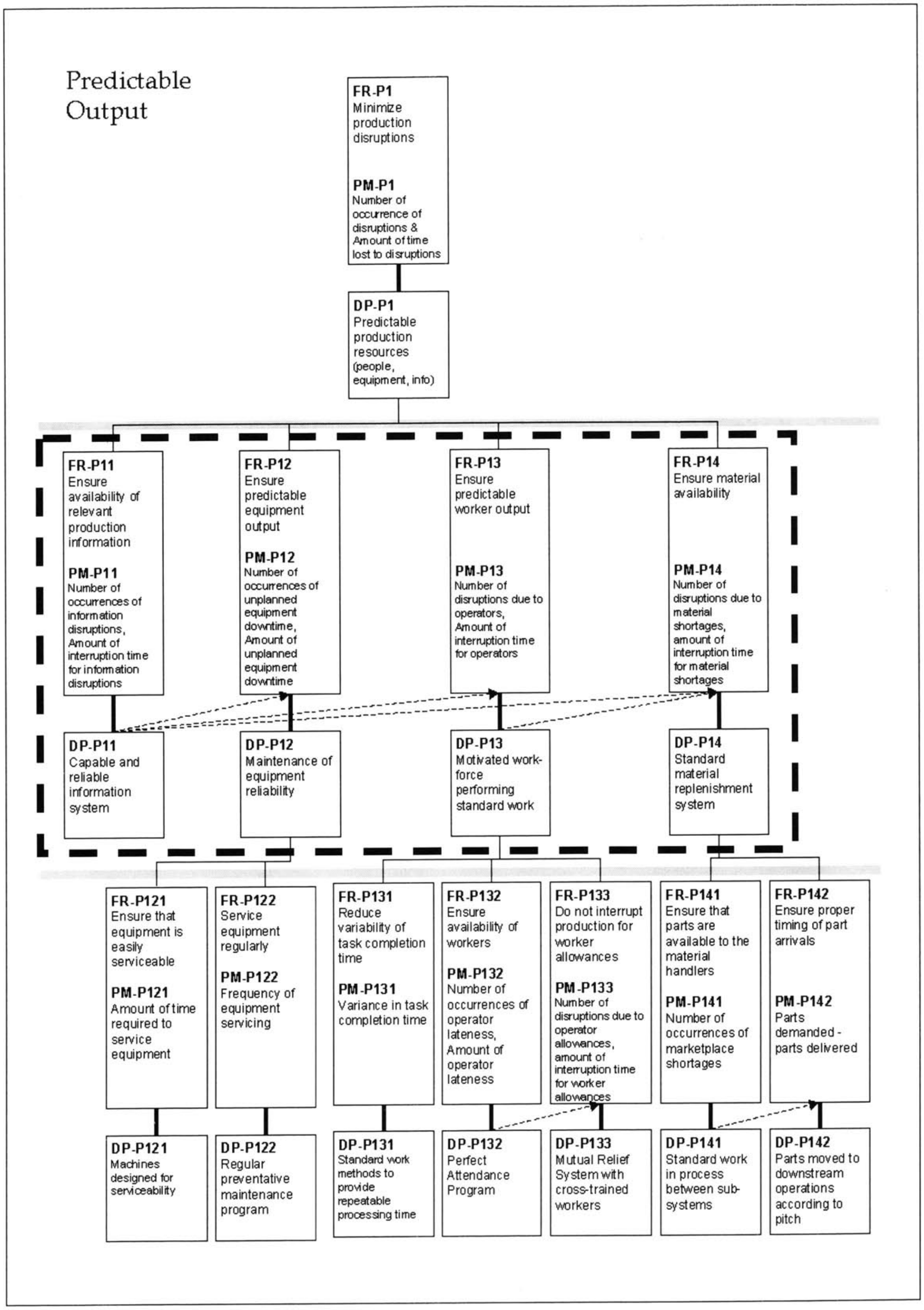
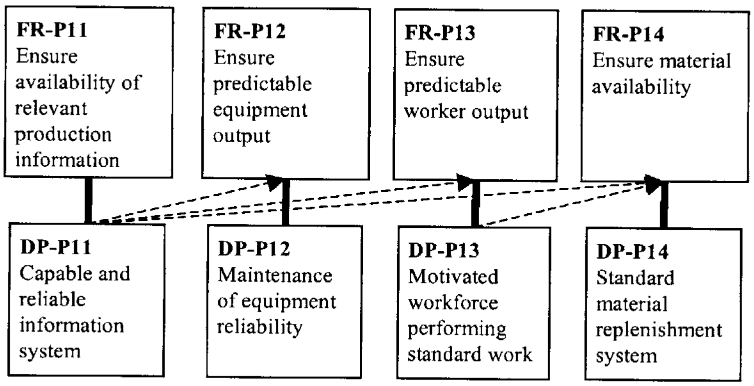


Figure 3.10: Predictable Output Branch of the MSDD

In order to accomplish DP-P1, four different aspects of the system design must be available and predictable: production information, equipment, operators, and materials. The example which follows illustrates the middle level FR-DP pairs of the Predictable Output branch, specifically FRs-P11, P12, P13, and P14 which are shown in Figure 3.11 along with the design matrix.



$$\begin{Bmatrix} FR\text{-}P11 \\ FR\text{-}P12 \\ FR\text{-}P13 \\ FR\text{-}P14 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ X & X & O & O \\ X & O & X & O \\ X & O & X & X \end{bmatrix} \begin{Bmatrix} DP\text{-}P11 \\ DP\text{-}P12 \\ DP\text{-}P13 \\ DP\text{-}P14 \end{Bmatrix}$$

Figure 3.11: Middle Level of the Predictable Output Branch with the Design Matrix

These four aspects are depicted in a fishbone diagram in Figure 3.12 [Montgomery, 1985]. The production resources of the system design must be predictable, and this branch is further decomposed into more specific functional requirements and design parameters which lead to predictable output. With predictable production resources, the variation in the throughput time of the system will also be reduced, which again corresponds to the upper level DP 112: Throughput time variation reduction.

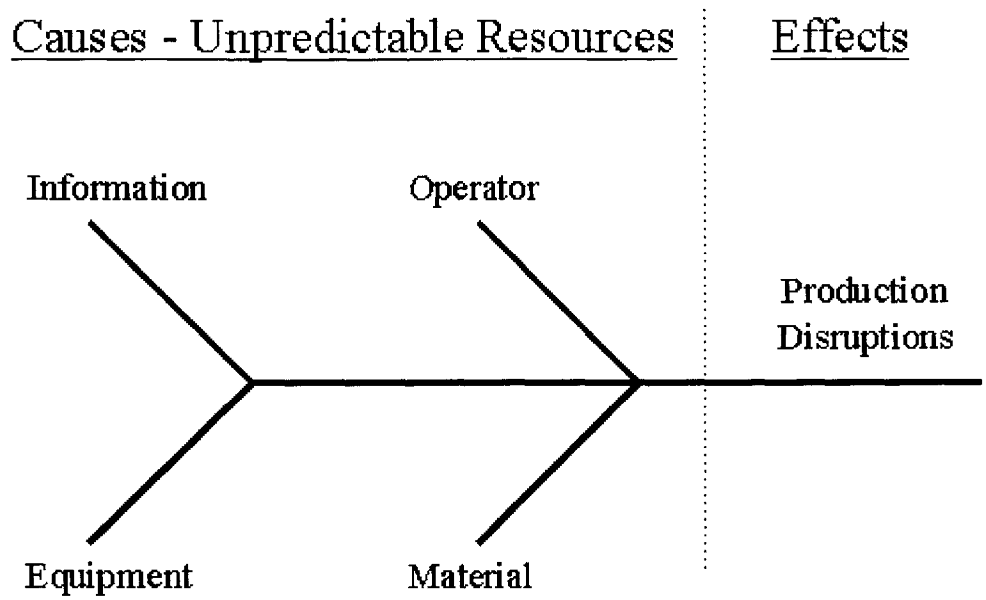


Figure 3.12: Fishbone Diagram Showing Unpredictable Resources Causing Production Disruptions

3.3.4 Delay Reduction Branch

The Delay Reduction branch of the Manufacturing System Design Decomposition shown in Figure 3.13 decomposes the following FR-DP pair:

FR 113: Meet customer expected lead time

DP 113: Mean throughput time reduction

In order to accomplish DP 113, five types of delays must be reduced: lot, process, run size, transportation, and systematic operational delays. These five delays are further decomposed into more specific functional requirements and design parameters which lead to reductions in each of the delays. By reducing all types of delays, the mean throughput time of the manufacturing system can be reduced.

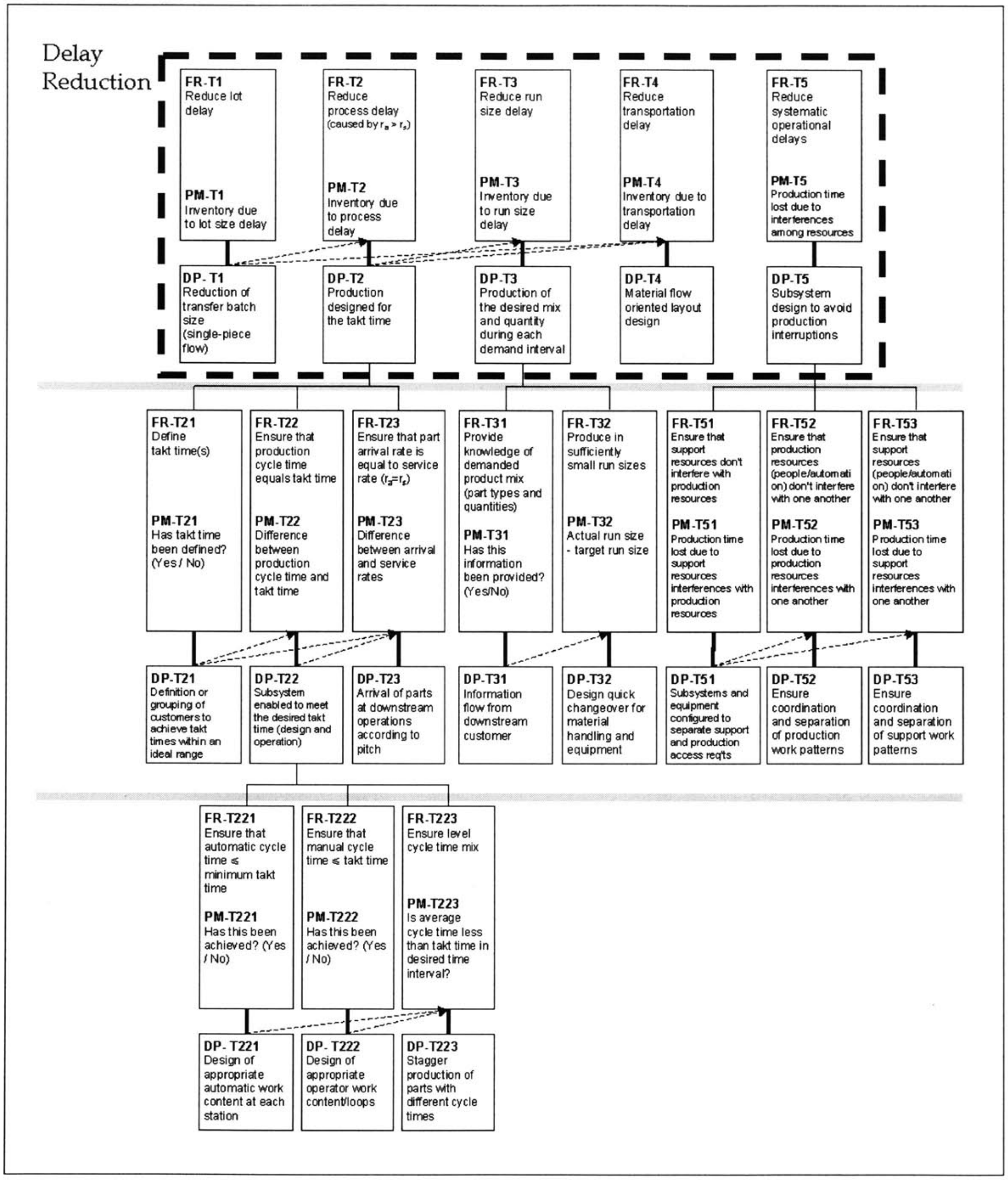


Figure 3.13: Delay Reduction Branch of the MSDD

The examples which follow in this section illustrate the top level FR-DP pairs of the Delay Reduction branch, specifically FRs-T1, T2, T3, T4, and T5 which are shown in Figure 3.14 along with the design matrix.

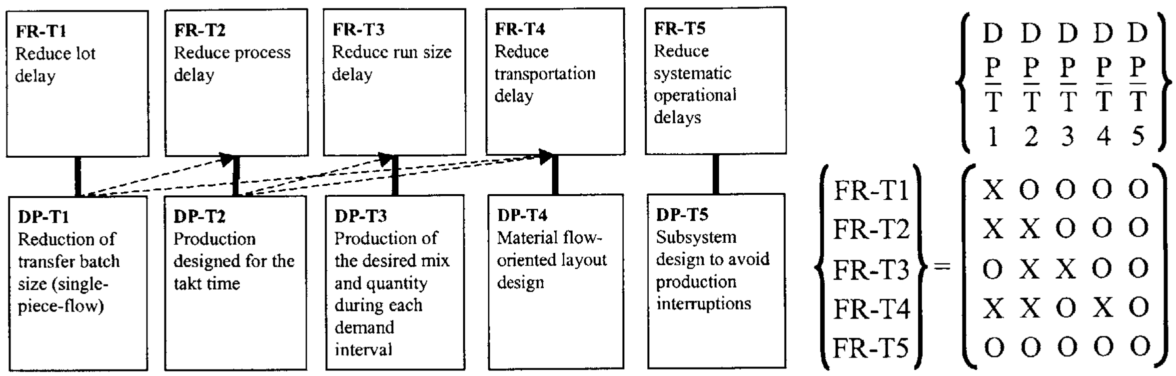


Figure 3.14: Top Level of the Delay Reduction Branch with the Design Matrix

Lot delay is the time wasted when parts in a single lot (or batch) wait on others in the same lot to be processed. Reducing the lot size will reduce this delay, and single-piece flow will completely eliminate lot delay. Figure 3.15 illustrates production with a batch size of either 600 units or one unit and their resulting throughput times.

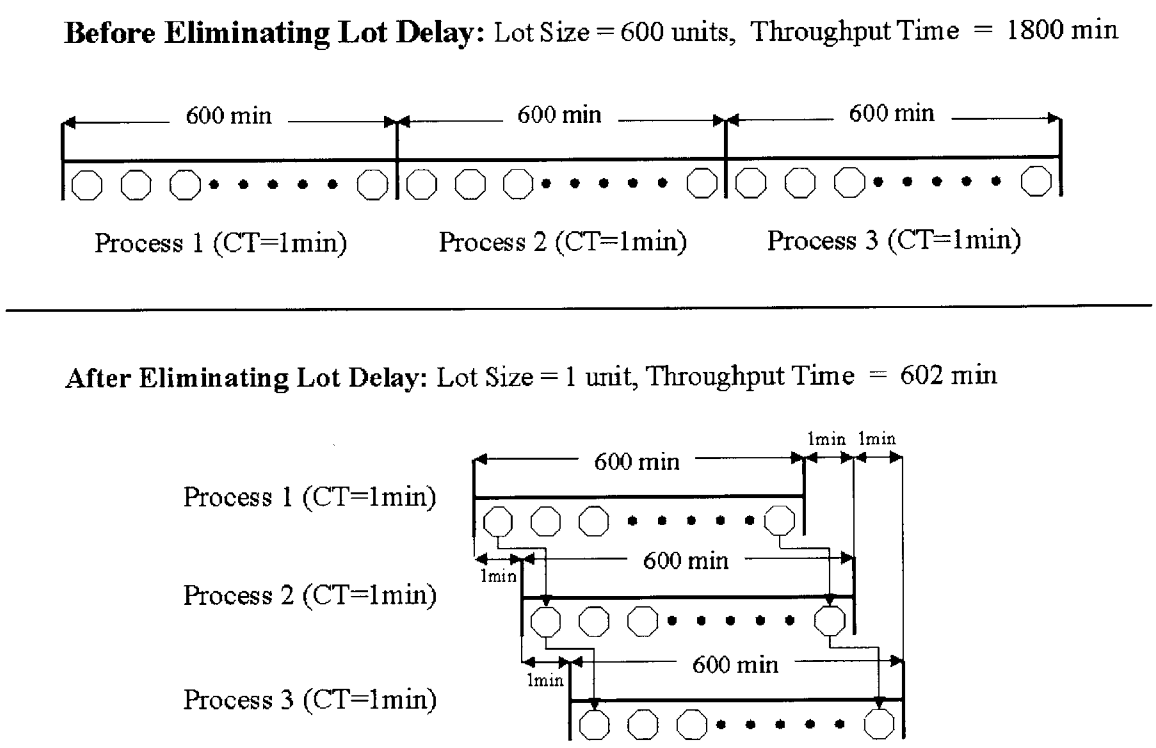


Figure 3.15: Example of Eliminating Lot Delay (Cochran et. al., 1999)

Process delay is the time wasted when an entire lot (or batch) waits for a different lot to finish at a single process. If the arrival rate of parts at a station or operation is greater than the processing rate at the station, there will be process delay. Figure 3.16 shows two scenarios of a set of operations; one scenario has balanced operations while the other scenario has unbalanced operations, resulting in process delay.

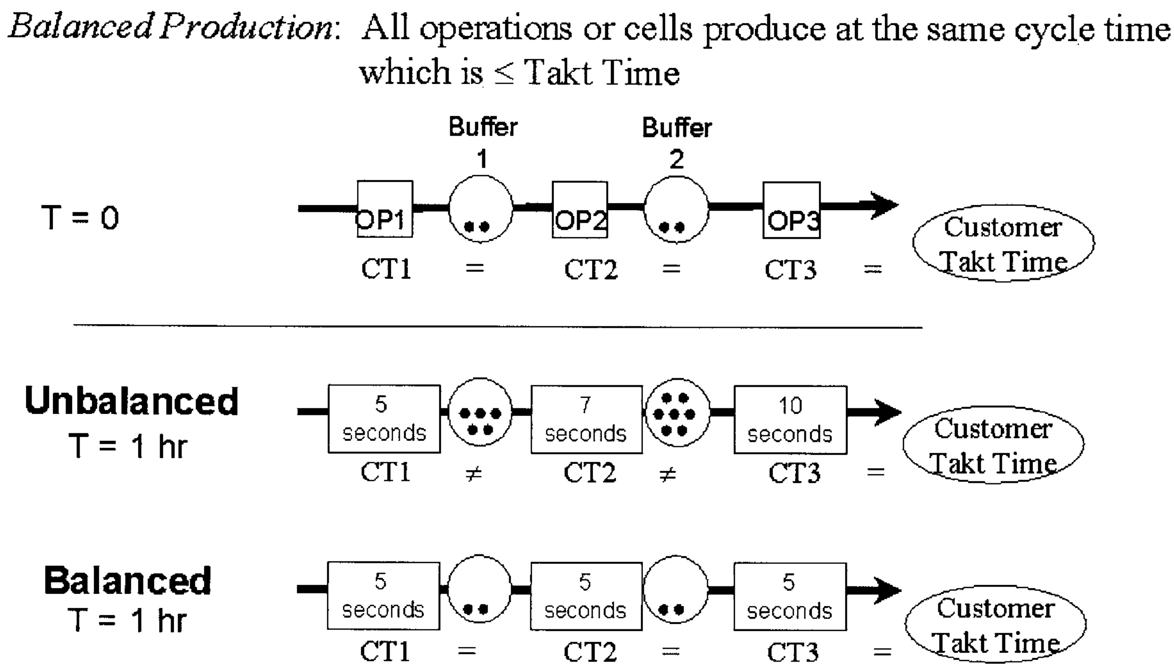


Figure 3.16: Example of Eliminating Process Delay [Linck, 1996]

Run size delay is the time wasted waiting for a part type to be produced because the system is full of parts of a different part type. In order to reduce run sizes, the issue of changeovers / setup-times must be addressed. Typically, run sizes are very large in order to reduce the number of time-consuming changeovers necessary, but the large run sizes make the manufacturing system unresponsive. Reducing run sizes will allow the manufacturing system to be more responsive to customer demand. Mixing the production of different part types with reduced run sizes is called leveling. Figure 3.17 portrays the difference between unleveled and leveled production.

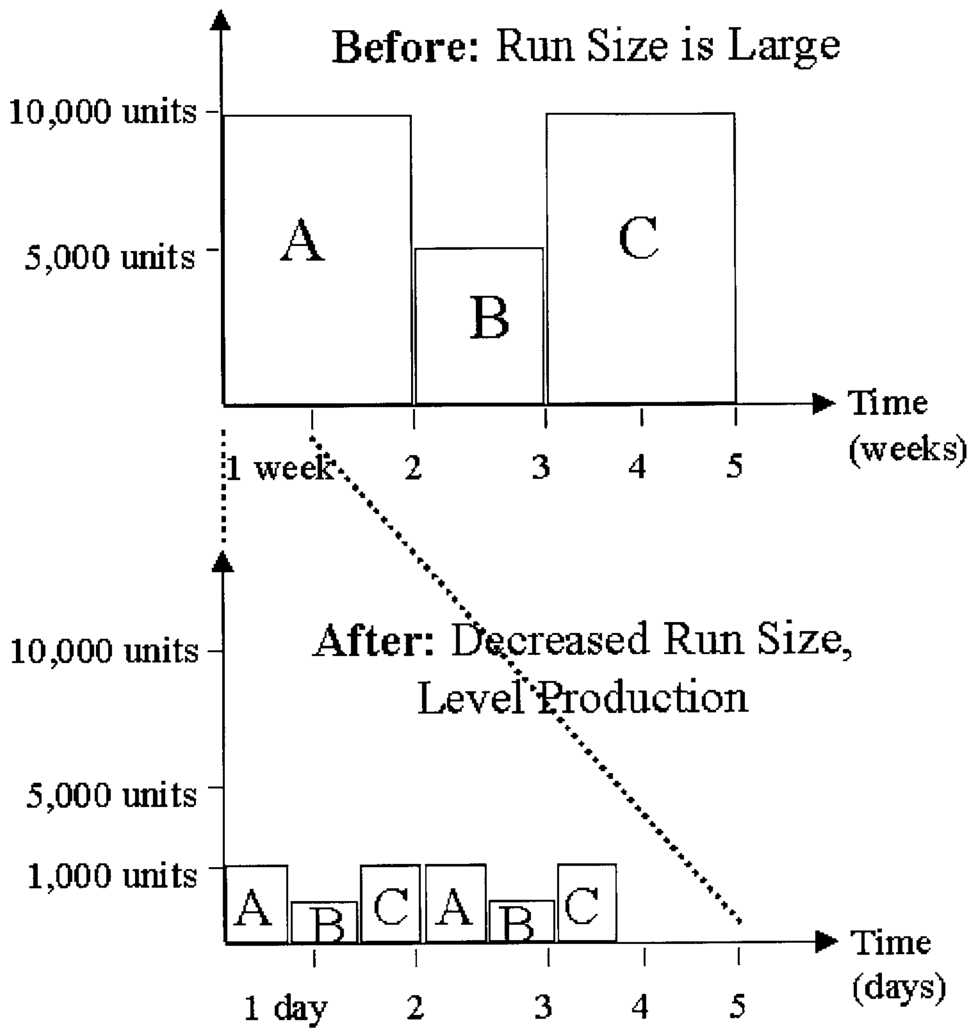


Figure 3.17: Example of Eliminating Run Size Delay (Cochran et. al., 1999)

Transportation delay is the time wasted transporting parts between machines/stations. This delay can be greatly reduced by laying out the manufacturing system with the material flow in mind. Figure 3.18 depicts a plant which has not been laid out with the material flow in mind. The parts travel very long distances between machines and waiting areas throughout the entire plant.

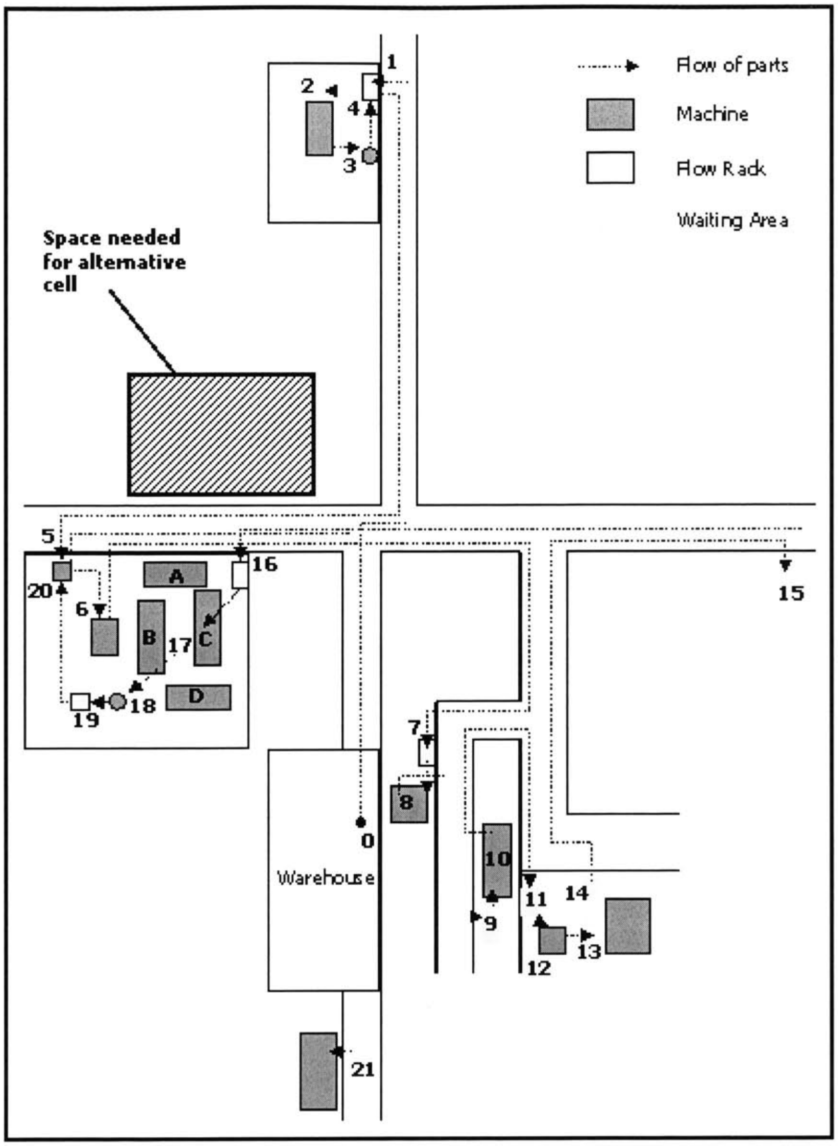


Figure 3.18: Example of Wasted Transportation [Weidemann, 1998]

Systematic operational delay is the time wasted when production or support resources interfere with themselves or each other. Production resources may interfere with each other if, for example, two operators need to use the same machine at the same time. Support resources may interfere with each other if, for example, material replenishers cross paths as they try to replenish the production resources. Finally, support resources may interfere with production resources if, for example, material replenishers interrupt production while stocking material. Figure 3.19 shows how material replenishment can be designed to avoid interrupting production operators.

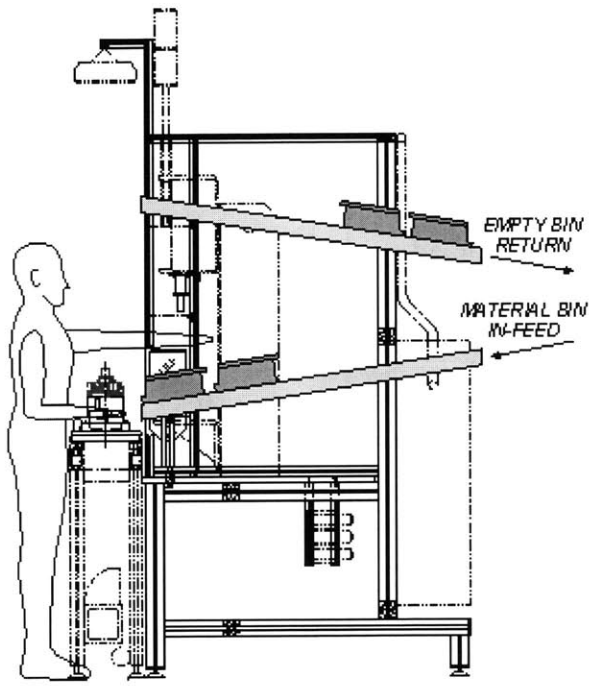


Figure 3.19: Example of Eliminating Systematic Operational Delay [Collins, 1999]

3.3.5 Direct Labor Branch

The Direct Labor branch of the Manufacturing System Design Decomposition shown in Figure 3.20 decomposes the following FR-DP pair:

FR 121: Reduce waste in direct labor

DP 121: Elimination of non-value adding manual tasks

In order to accomplish DP 121, all types of wastes related to the operators must be eliminated. Three types of wastes in direct labor have been identified: waiting on machines, unnecessary motions, and waiting on operators. The operators' time and skills are very valuable, and great efforts should be made to utilize the workforce effectively and to avoid non-value adding manual tasks. This branch is further decomposed into more specific functional requirements and design parameters which lead to elimination of non-value adding manual tasks in direct labor.

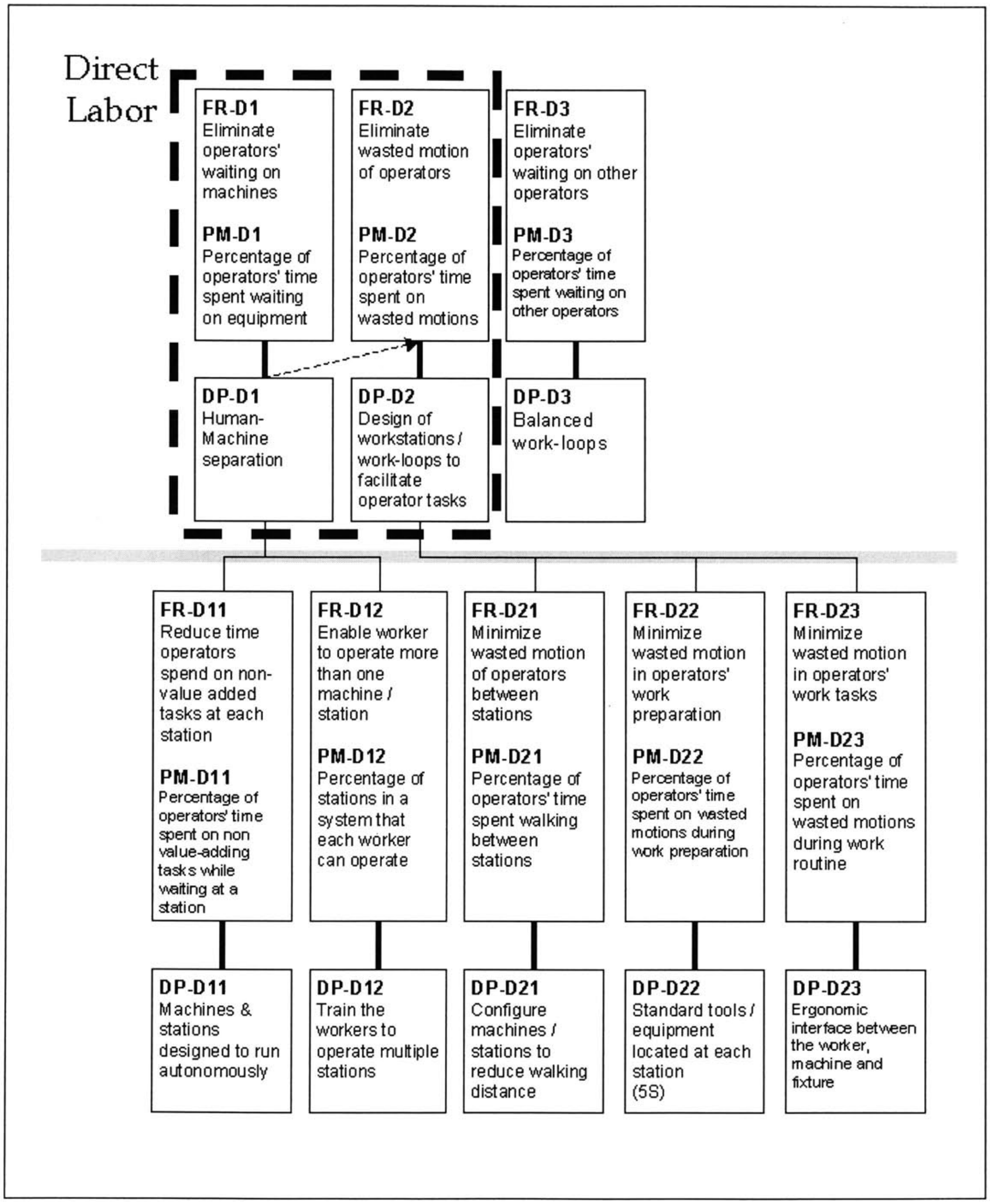
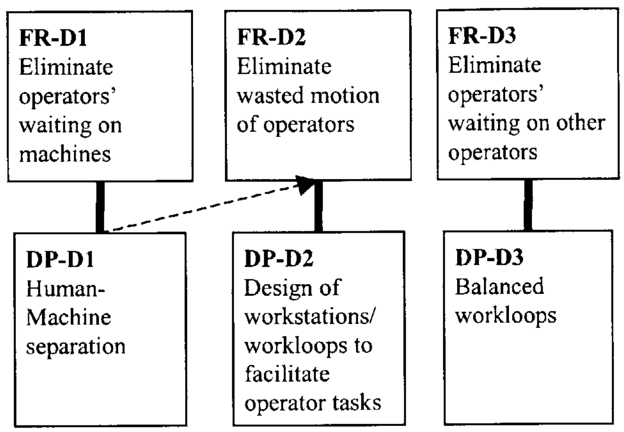


Figure 3.20: Direct Labor Branch of the MSDD

The examples which follow illustrate the top level FR-DP pairs of the Direct Labor branch, specifically FRs-D1 and D2 which are shown in Figure 3.21 along with the design matrix.



$$\left\{\begin{matrix} \frac{DP}{D1} & \frac{DP}{D2} & \frac{DP}{D3} \end{matrix}\right\}$$

$$\left\{\begin{matrix} FR\text{-}D1 \\ FR\text{-}D2 \\ FR\text{-}D3 \end{matrix}\right\} = \begin{bmatrix} X & O & O \\ X & X & O \\ O & O & X \end{bmatrix}$$

Figure 3.21: Top Level of the Direct Labor Branch with the Design Matrix

Figure 3.22 shows two different layouts to manufacture the same parts. In the upper layout, operators are tied to individual machines/stations because the machines/stations are not designed to run autonomously; however, in the lower layout, operators may work at several machines/stations in a designated workloop because human-machine separation has been achieved by redesigning the machines/stations.

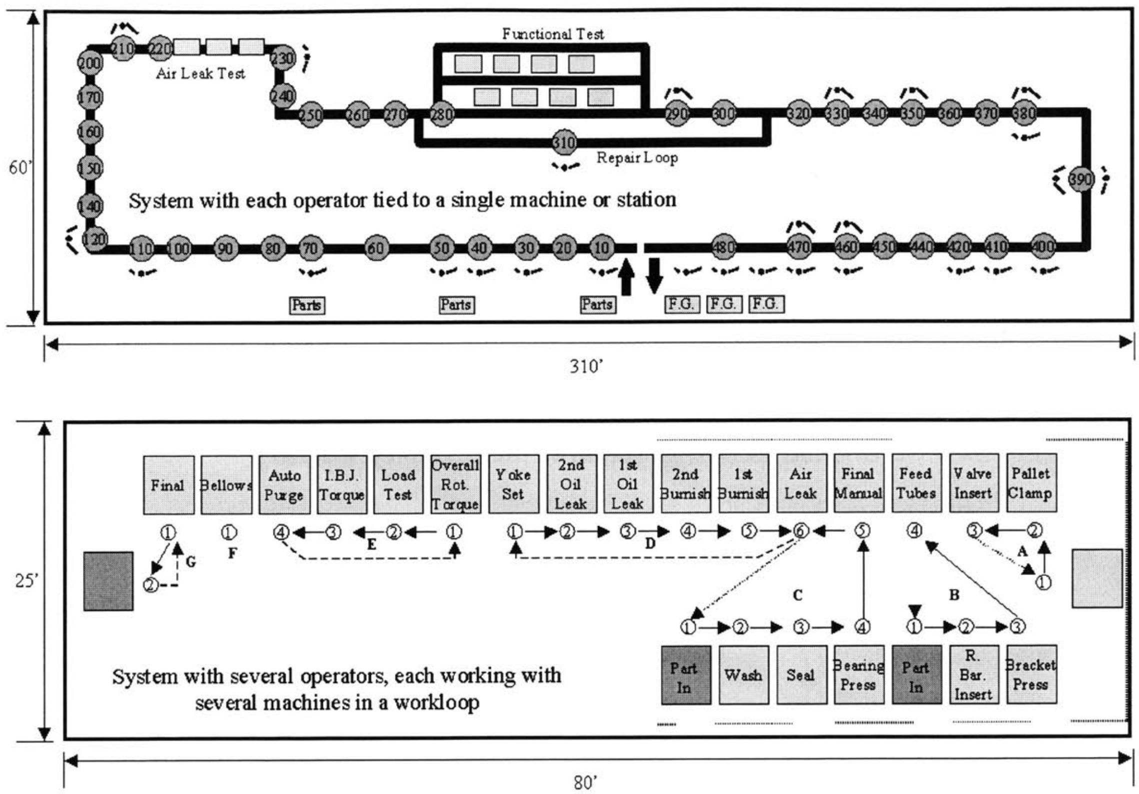
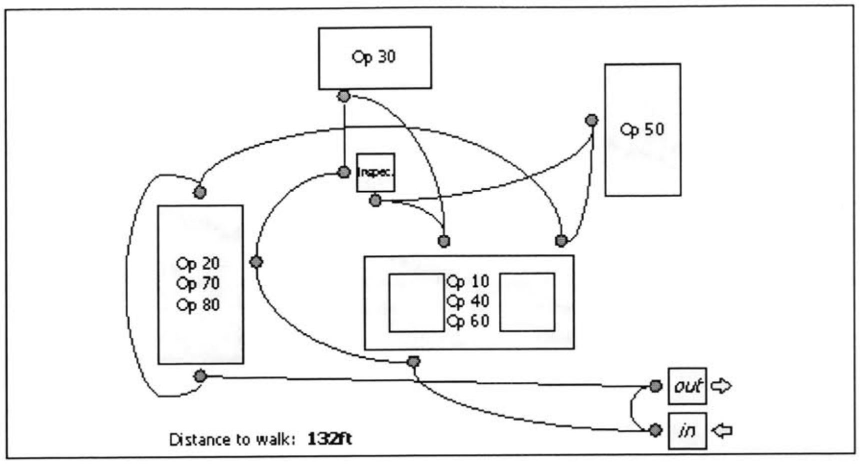
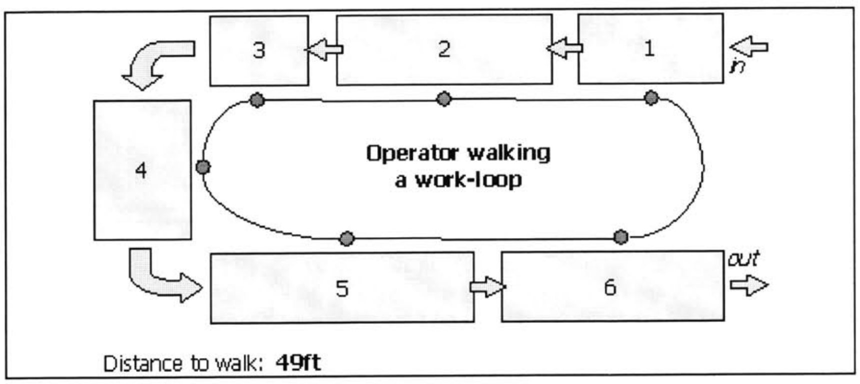


Figure 3.22: Two Different Manufacturing Layouts: One Showing Operators Tied to Machines and the Other Showing Human-Machine Separation [Cochran, Dobbs, 1999]

Figure 3.23 illustrates two different layouts to manufacture the same parts as well. In the upper layout, the operator is forced to walk a complicated workpath because the machines are not laid out according to material flow; however, in the lower layout, the operator walks a simple workloop because the machines are laid out according to the flow of material through the machines/stations.



Workstation design requires unnecessary walking



Workstation/workloop design minimizes walking

Figure 3.23: Two Different Manufacturing Layouts: One Showing Poor Workloop Design and the Other Showing Good Workloop Design (Cochran et. al., 1999)

3.3.6 Indirect Labor Branch

The Indirect Labor branch of the Manufacturing System Design Decomposition shown in Figure 3.24 decomposes the following FR-DP pair:

FR 122: Reduce waste in indirect labor

DP 122: Reduction of indirect labor tasks

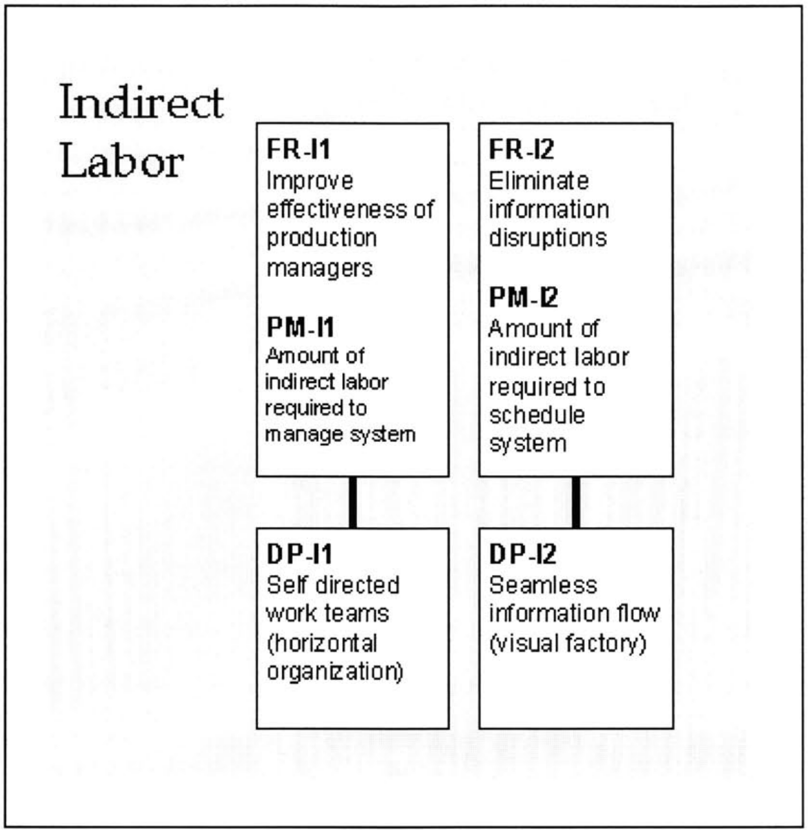


Figure 3.24: Indirect Labor Branch of the MSDD

In order to accomplish DP 122, production must be managed more effectively, and production scheduling information should be available and reliable. One method to achieve this objective is flattening the vertical hierarchy within a manufacturing system so that information is exchanged quickly between managers and operators. When information flows quickly and easily, the wastes in indirect labor tasks will be greatly reduced.

The example which follows illustrates FR-I1 of the Indirect Labor branch, which is shown in Figure 3.25 along with the design matrix.

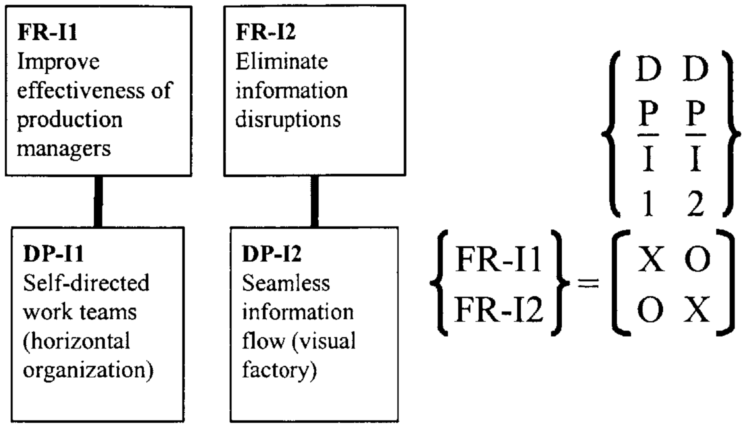


Figure 3.25: Top Level of the Indirect Labor Branch with the Design Matrix

Figure 3.26 graphically depicts the difference between vertical organization and horizontal organization. Vertical organization emphasizes employees' job functions instead of the product model on which they are working. Horizontal organization emphasizes diverse teams of people working on each product model to encourage greater cooperation.

Before: Vertical Organization Arranged by Function

		Function			
		Production Manager	Materials,Planning, and Logistics	Quality Assurance	Maintenance
	A	Bob	Jane	Sam	Greg
Product	B	John	Chris	Dan	Karen
Model	C	Laura	Monica	Tara	Rich
	D	Tom	Sally	Francis	Pat

After: Horizontal Organization Arranged by Product Model
Self-directed work teams

		Function			
		Production Manager	Materials,Planning, and Logistics	Quality Assurance	Maintenance
	A	Bob	Jane	Sam	Greg
Product	B	John	Chris	Dan	Karen
Model	C	Laura	Monica	Tara	Rich
	D	Tom	Sally	Francis	Pat

Figure 3.26: Vertical Organization vs. Horizontal Organization

3.4 Building the Production System Design Framework based on the Manufacturing System Design Decomposition

The Manufacturing System Design Decomposition is the first and most crucial element of the Production System Design (PSD) Framework, shown in Figure 3.27. The PSD Framework is made up of several elements which are all built upon the Axiomatic Design methodology, the basis for manufacturing system design and implementation-path dependency [Suh, Cochran, Lima, 1998]. Using this framework, manufacturing systems can be designed, implemented, and evaluated in terms of the effectiveness in satisfying the long-term system objectives.

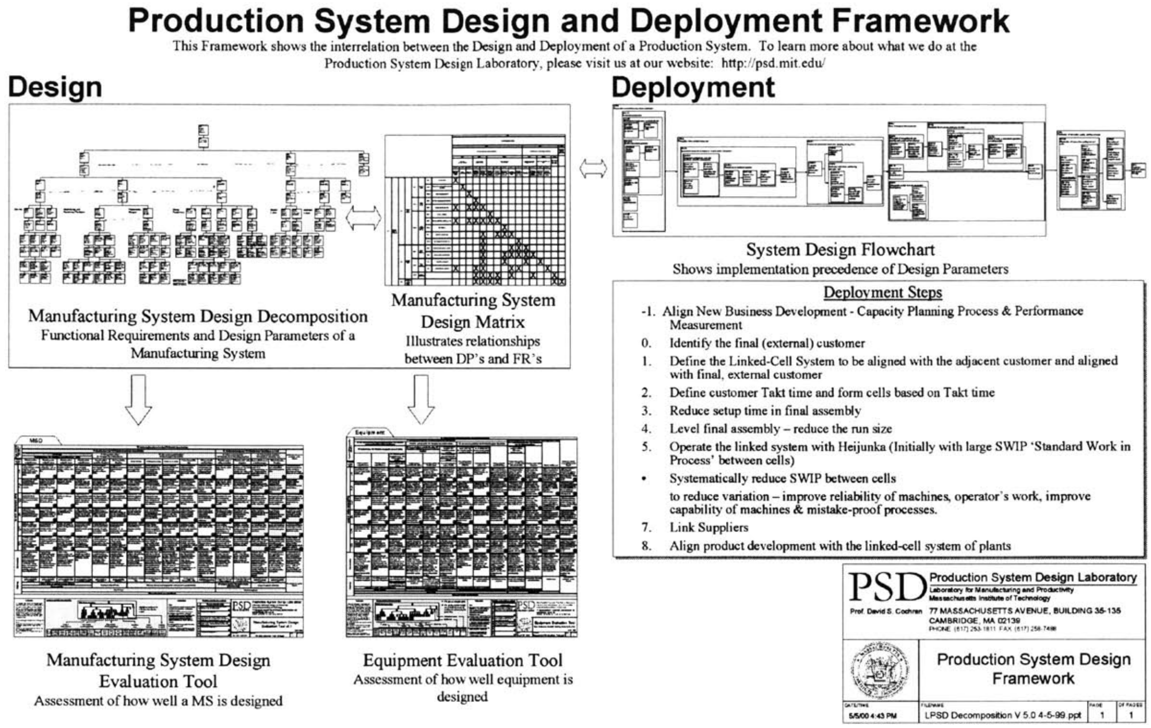


Figure 3.27: Production System Design Framework

The PSD Framework consists of the following elements:

Manufacturing System Design Decomposition,

Manufacturing System Design Matrix,

Manufacturing System Design Implementation Flowchart,

Manufacturing System Design Evaluation Tool,

Equipment Evaluation Tool, and

Manufacturing System Design Deployment Steps.

All of the above elements of the PSD Framework are developed based on the MSD Decomposition [Cochran, 1999]. Each of these elements is briefly described in the following sections.

3.4.1 Manufacturing System Design Matrix

The Manufacturing System Design Matrix shown in Figure 3.28 is developed concurrently with the MSD Decomposition. During the decomposition process when

DPs are chosen to satisfy FRs, the relationships between the DPs and FRs is determined. These relationships create a design matrix for each level of FR-DP pairs. The MSD Matrix is a composite of all matrices for the top four levels of the MSD Decomposition. It shows, at a glance, which DPs affect which FRs of the manufacturing system design.

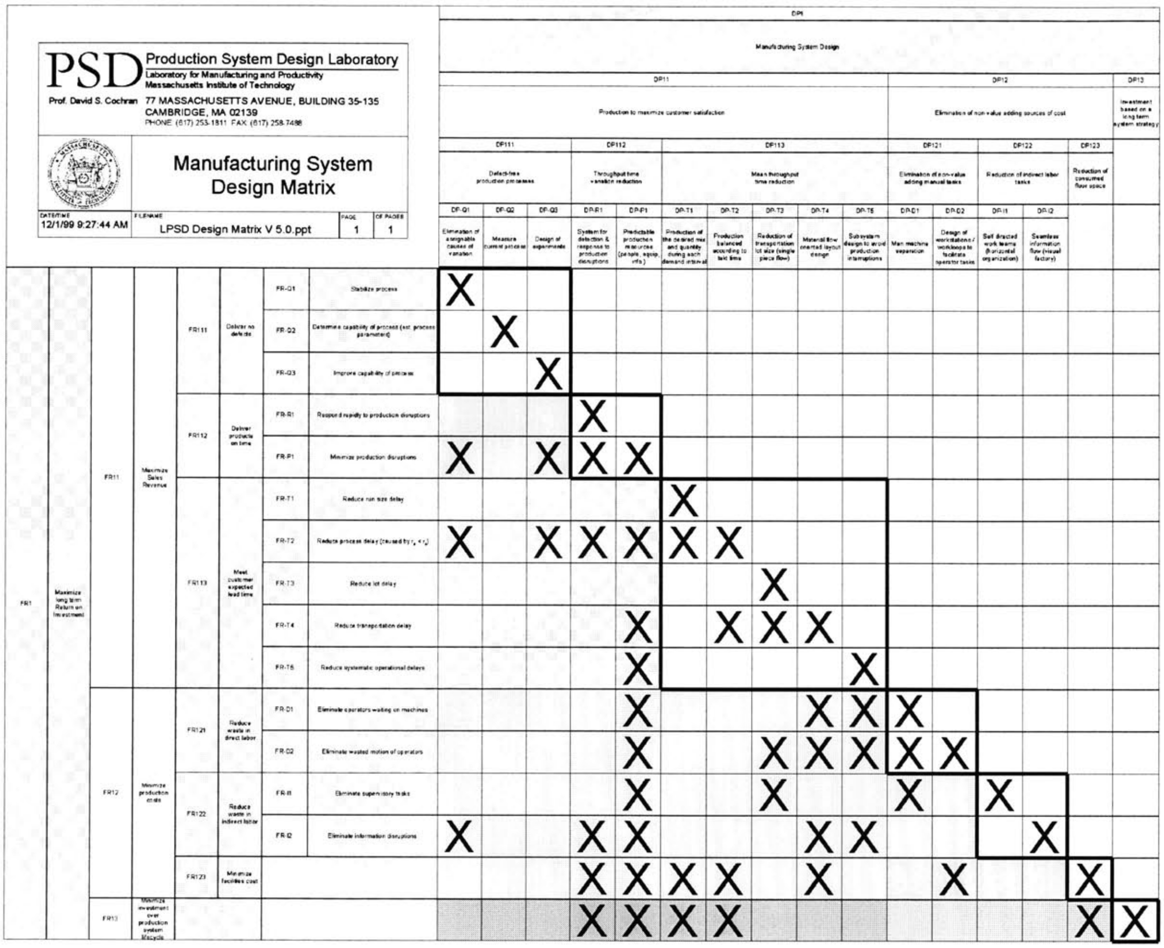


Figure 3.28 Manufacturing System Design Matrix

The rows of the MSD Matrix correspond to the top four levels of FRs of the MSD Decomposition, and the columns of the MSD Matrix correspond to the top four levels of DPs. An 'X' in a box of the matrix represents dependence whereas an empty box represents independence. The MSD Matrix shows very clearly that the manufacturing system design is decoupled, as defined by Axiomatic Design [Suh, 1990]. Because the manufacturing system design is decoupled, there exists an optimal order of implementation which, when followed, will allow all the FRs of the design to be satisfied. The Matrix can now be used to aid in the development of the other elements of the PSD Framework.

3.4.2 Manufacturing System Design Implementation Flowchart

The Manufacturing System Design Implementation Flowchart shown in Figure 3.29 is developed based on both the MSD Decomposition and the MSD Matrix. The MSD Implementation Flowchart uses the decoupled nature of the MSD Matrix in order to provide an order of implementation for the design parameters (DPs).

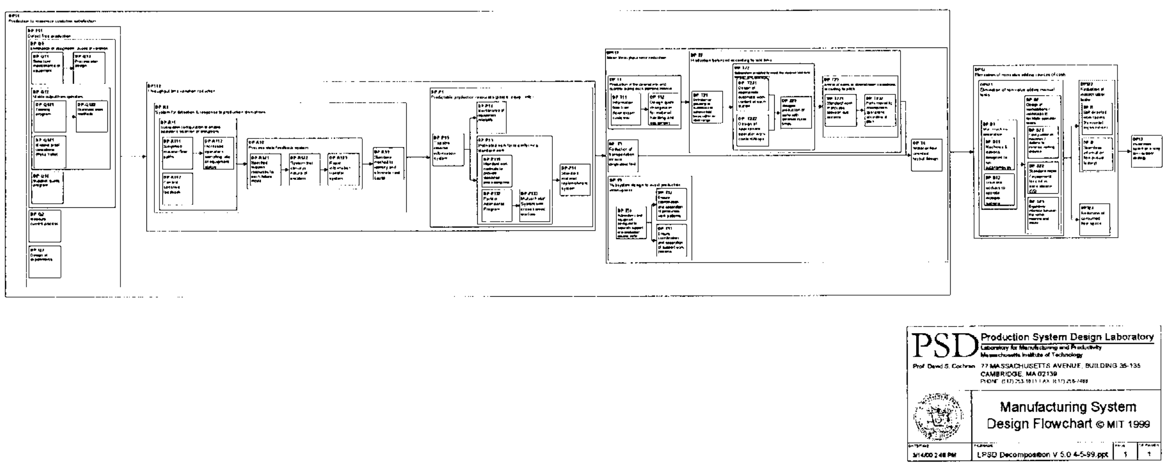


Figure 3.29: Manufacturing System Design Implementation Flowchart

In general, implementation begins at the left side of the MSD Implementation Flowchart and proceeds to the right. However, for each large section, the innermost boxes should be implemented first and proceed outward from the innermost box. This implementation procedure should continue until all boxes have been implemented. The sections of the implementation flowchart are shown in Figures 3.30-3.34.

The implementation order for the Quality section of the MSD Implementation Flowchart shown in Figure 3.30 will be discussed as an example. First, a training program must be put in place to train all the operators. Then, standard work methods should be defined and followed by all operators. Operations can be mistake-proofed simultaneously with the development of a training program and standard work methods. After accomplishing all of these things, the output from the operators will be much more stable. Next, failure modes and effects analysis can be used to eliminate assignable causes of variation from machines. Then, process plans should be designed so that work methods are no longer assignable causes of variation. A supplier quality program should be implemented simultaneously with FMEA and process plan design so that assignable causes of variation from incoming materials are eliminated. Once all of these things are achieved, most assignable causes of variation from equipment, operators, methods, and materials will have been eliminated from the manufacturing system. Then, process parameters should be adjusted so that the processes are centered on the target mean, and process noise should be reduced so that there is less variation in the process output. By accomplishing all of these things, the highest level DP 'Production processes with minimal variation from the target' can be achieved. Each of the remaining sections of the MSD Implementation Flowchart can be implemented using this example as a guide. The idea of standardization is prevalent throughout the flowchart because it is very important to the design of a manufacturing system.

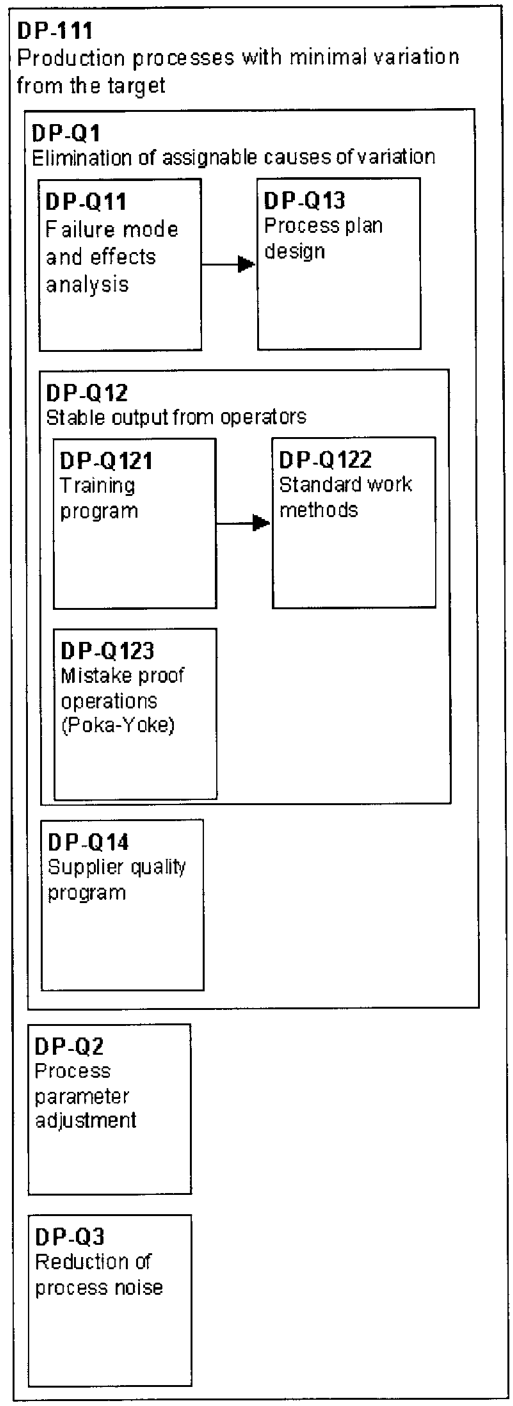


Figure 3.30: Quality Section of the MSD Implementation Flowchart

The Identifying and Resolving Problems section of the MSD Implementation Flowchart is shown in Figure 3.31. Notice that DP-R13 requires a standard method to identify and eliminate root causes of production disruptions in a manufacturing system.

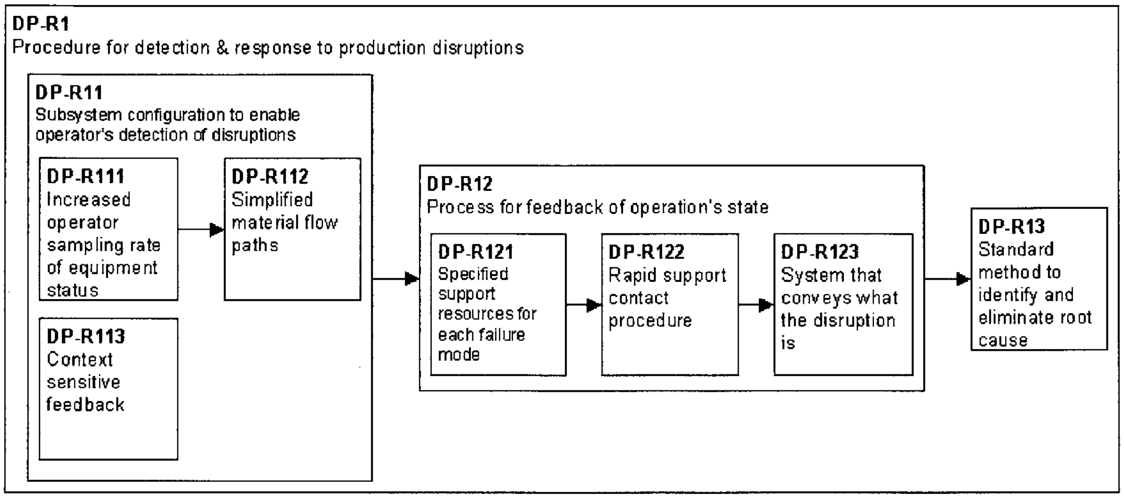


Figure 3.31: Identifying and Resolving Problems Section of the MSD Implementation Flowchart

The Predictable Output section of the MSD Implementation Flowchart is shown in Figure 3.32. Notice that DP-P131 and DP-P14 require standard work methods to achieve repeatable processing times and a standard material replenishment system, respectively.

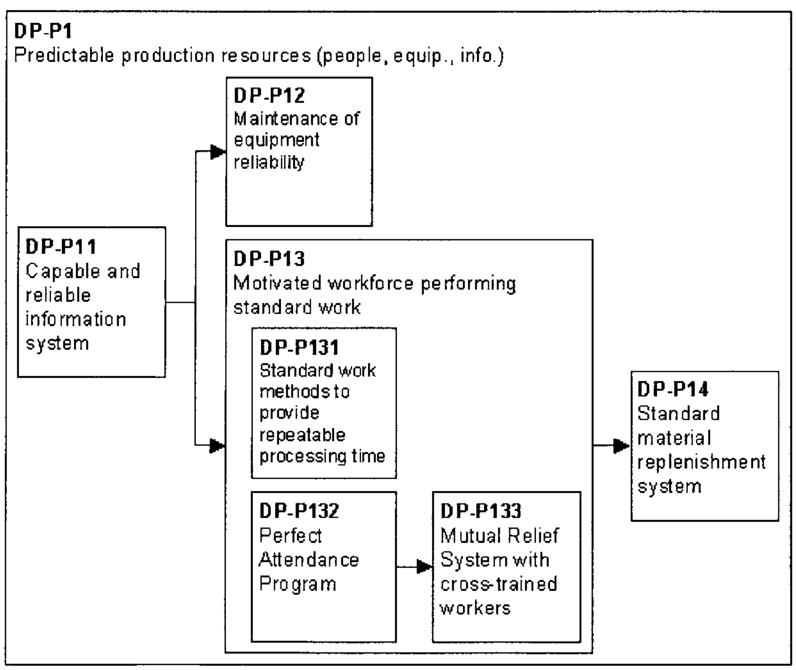


Figure 3.32: Predictable Output Section of the MSD Implementation Flowchart

The Delay Reduction section of the MSD Implementation Flowchart is shown in Figure 3.33. Notice that DP-T4 specifies a simplified, material flow-oriented layout design which is very key to a manufacturing system design.

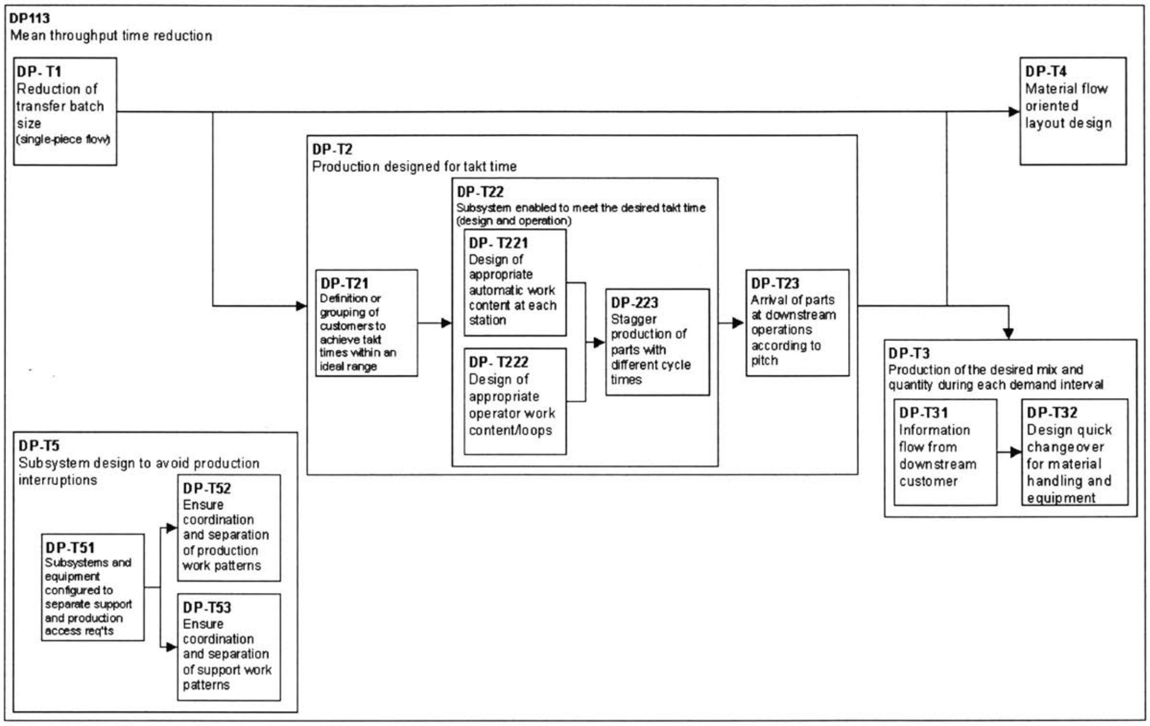


Figure 3.33: Delay Reduction Section of the MSD Implementation Flowchart

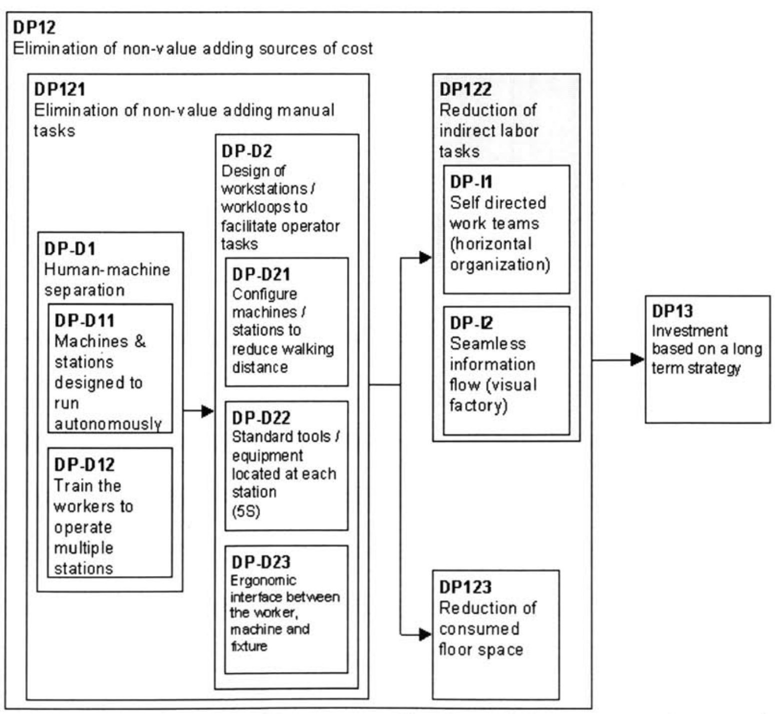


Figure 3.34: Manufacturing Costs and Investment Section of the MSD Implementation Flowchart

The Manufacturing Costs and Investment section of the MSD Implementation Flowchart is shown in Figure 3.34. Notice that DP-D22 requires standard tools and equipment located at the workstations. Also, DP-I2 specifies a seamless, visual information flow design which is very key to a manufacturing system design, similar to simplified material flow design.

In order to facilitate implementation, the PSD Framework includes Deployment Steps as well as the MSD Implementation Flowchart. The MSD Deployment Steps will be discussed in a separate section.

3.4.3 Manufacturing System Design Evaluation Tool

The Manufacturing System Design Evaluation Tool shown in Figure 3.35 is developed based on the MSD Decomposition [Wang, 1999 and Cochran, Chu, 2000]. An extremely important distinction that must be made is that the MSD Evaluation Tool is intended to evaluate the design of a manufacturing system, not its performance. This tool, for the most part, uses the level 4 FRs of the MSD Decomposition as criteria to evaluate the design of a manufacturing system.

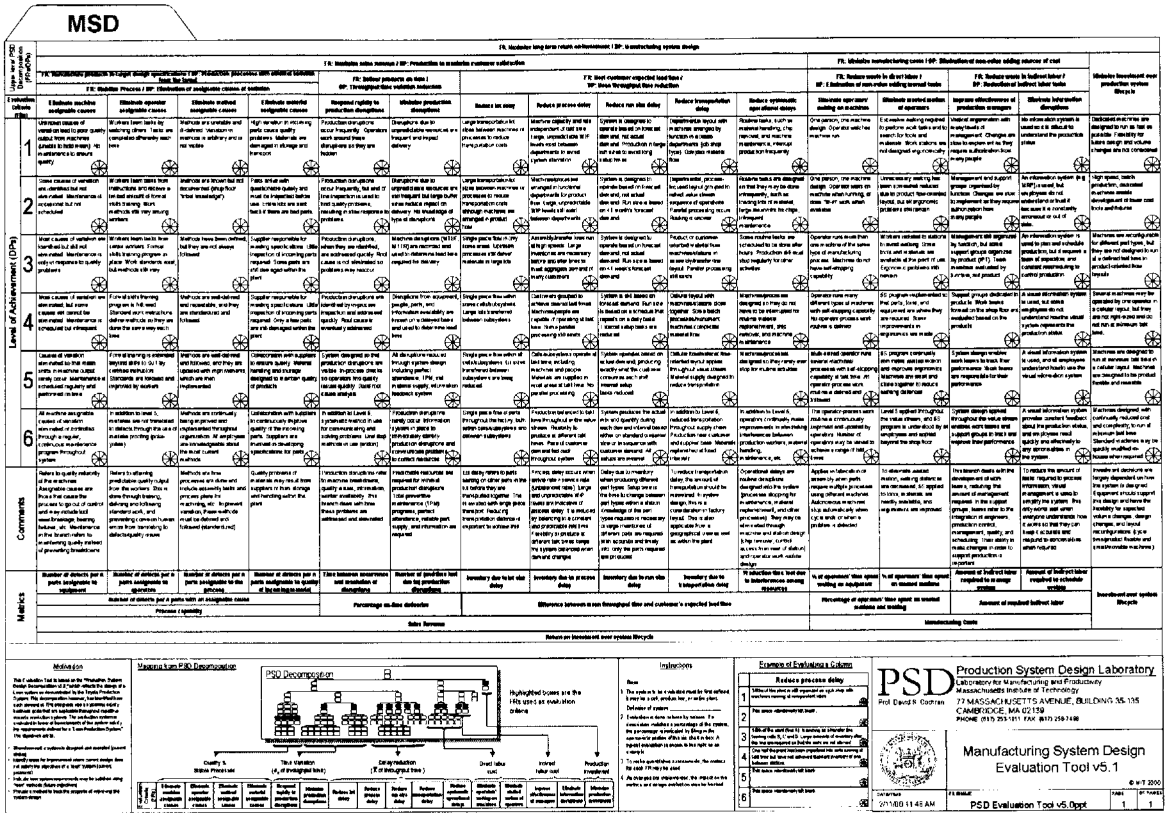


Figure 3.35: Manufacturing System Design Evaluation Tool

Each of the evaluation criteria corresponds to a single column of the MSD Evaluation Tool. For each column, six possible levels of achievement are defined with descriptive excerpts. Level 1 achievement is basic 'mass' manufacturing, and level 6 achievement is excellent 'lean' manufacturing. It is possible to have part of a system designed at level 3 and another part of the same system designed at level 5; therefore, the qualitative pie chart scoring method allows evaluation of such diverse systems. When making improvements to a system design, the MSD Matrix should be used with this Evaluation Tool in order to identify how improvement efforts may impact other parts of the manufacturing system design. Also, at the bottom of each column are quantitative performance metrics for each evaluation criterion, which will be discussed in the following section.

3.4.3.1 Performance Measurements

Performance Measurements (PMs) have been defined for each of the evaluation criteria in the MSD Evaluation Tool and are listed across the bottom of the chart. In addition, a performance measurement has been defined for every single FR in the MSD Decomposition. Some of these performance metrics are more important to track than others because they can provide more useful information regarding the performance of the manufacturing system. Also, some of them are tracked more easily than others in the system because some require much more data collection while the system is operating.

There are a total of about seventy performance measurements for the entire MSD Decomposition. The MSD Evaluation Tool lists less than twenty performance measurements at level 4 of the MSD Decomposition, along with all the upper level PMs. The goal is to pinpoint a small subset of the many performance measurements which are most important and useful to the design of a manufacturing system. This goal is the motivation for the later chapter on performance measurements.

3.4.4 Equipment Evaluation Tool

The Equipment Evaluation Tool [Gomez, 2000] shown in Figure 3.36 is developed based on the MSD Decomposition and is similar in structure to the MSD Evaluation Tool. This tool evaluates the design of equipment in order to make sure that the equipment supports the functional requirements of the manufacturing system design. The evaluation criteria for this tool have also been developed from the MSD Decomposition, similar to the MSD Evaluation Tool.

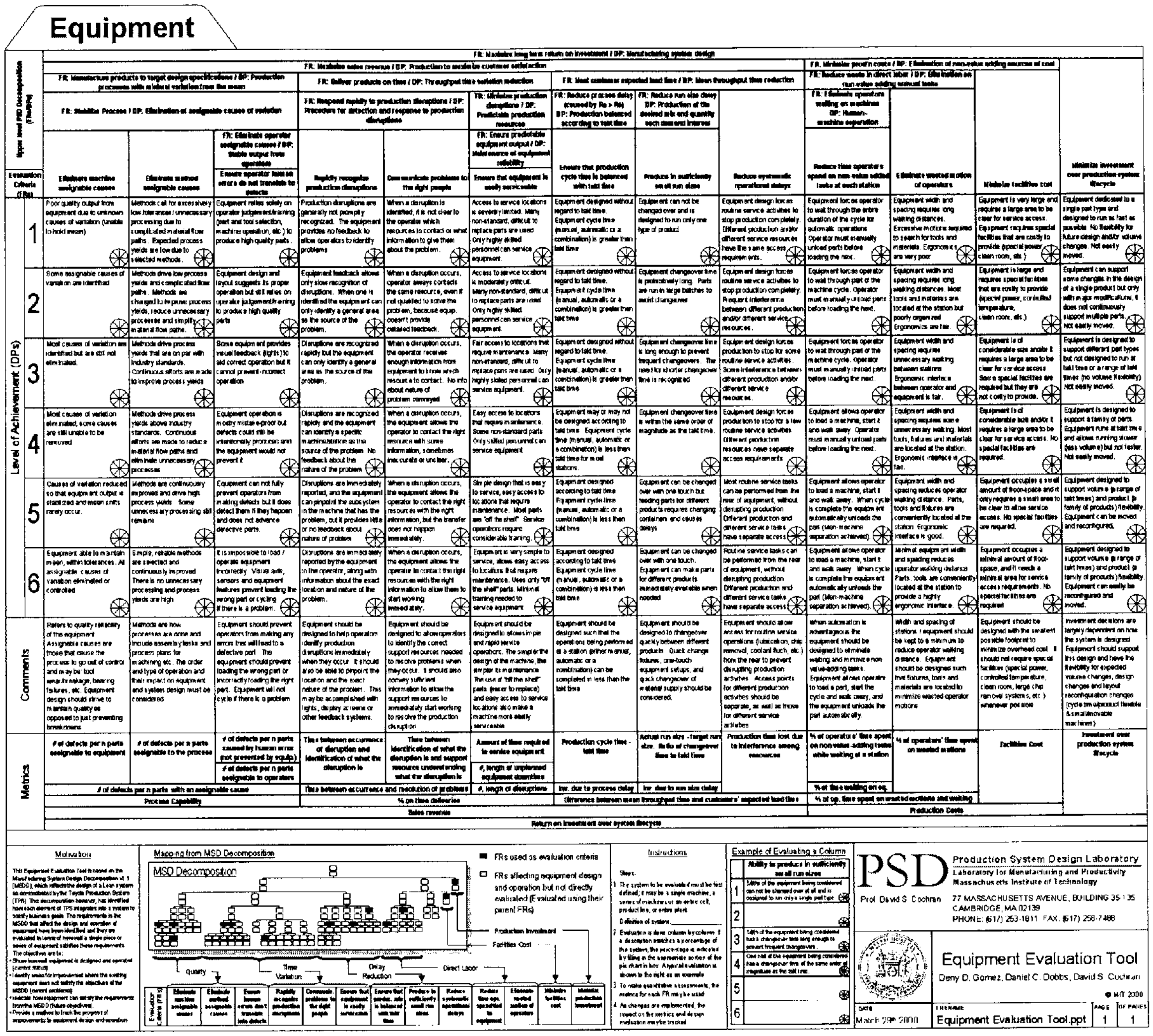


Figure 3.36: Equipment Evaluation Tool

Each of the evaluation criteria corresponds to a single column of the Equipment Evaluation Tool. For each column, six possible levels of achievement are defined with descriptive excerpts. Level 1 achievement is basic 'mass' manufacturing, and level 6 achievement is excellent 'lean' manufacturing. Again, the pie chart scoring method is used, similar to the MSD Evaluation Tool. Also, at the bottom of each column are quantitative performance metrics for each evaluation criterion.

3.4.5 Manufacturing System Design Deployment Steps

The Manufacturing System Design Deployment Steps shown in Figure 3.37 are intended to illustrate the general steps for proper implementation of a manufacturing system design. These steps are intended as a general guideline only, and it should be noted that proper implementation will likely differ based on the manufacturing environment and other factors specific to each system.

<u>Deployment Steps</u>

-1. Align New Business Development - Capacity Planning Process & Performance Measurement
0. Identify the final (external) customer
1. Define the Linked-Cell System to be aligned with the adjacent customer and aligned with final, external customer
2. Define customer Takt time and form cells based on Takt time
3. Reduce setup time in final assembly
4. Level final assembly – reduce the run size
5. Operate the linked system with Heijunka (Initially with large SWIP 'Standard Work in Process' between cells)
6. Systematically reduce SWIP between cells
   to reduce variation – improve reliability of machines, operator's work, improve capability of machines & mistake-proof processes.
7. Link Suppliers
8. Align product development with the linked-cell system of plants

Figure 3.37: Manufacturing System Design Deployment Steps

3.4.6 Applications

The Production System Design Framework consisting of the above elements has been used at several plants to convert from 'mass' manufacturing systems to 'lean' manufacturing systems. For this thesis, several Visteon plants have been evaluated using the MSD Evaluation Tool and the Performance Measurements. These plants include:

Chassis: Sterling, Monroe, and Indianapolis (2), and

Climate Control: Coclisa.

Using the MSD Evaluation Tool and the PMs to evaluate the design and performance of these manufacturing systems will serve as a validation of the PSD Framework in general. This validation is the motivation for the later chapters which discuss these applications.

3.5 Applicability Across Manufacturing Environments and Industries

The Manufacturing System Design Decomposition which has just been discussed makes a very important assumption from the outset. It is assumed that manufacturing system designs are independent of both volume and product type [Cochran, 1999]. This assumption means that the design of manufacturing systems is not influenced by the expected volume of production, nor is it influenced by the types of product to be produced by the manufacturing system, as long as the products are discrete, repetitively manufactured parts. With this assumption made, it is believed that the MSD Decomposition applies to most repetitive, discrete-part manufacturing systems.

Furthermore, it is postulated that the other sections of the Production System Design Framework are applicable to most repetitive, discrete-part manufacturing systems as well, because the Design Matrix, Implementation Flowchart, and Design Evaluation Tool are all derived based on the Manufacturing System Design Decomposition.

Chapter 4: Performance Measurements

4.1 *Introduction to Performance Measurements Derived from the MSD Decomposition*

Performance measurements (PMs) have been identified relating to each Functional Requirement (FR) of the MSD Decomposition shown in Figure 4.1. Beginning from Level 1 of the Decomposition down to Level 6, each FR has a corresponding PM. Graphically in the MSD Decomposition, each PM is designated just below its FR within the same box [Cochran et. al., 1999].

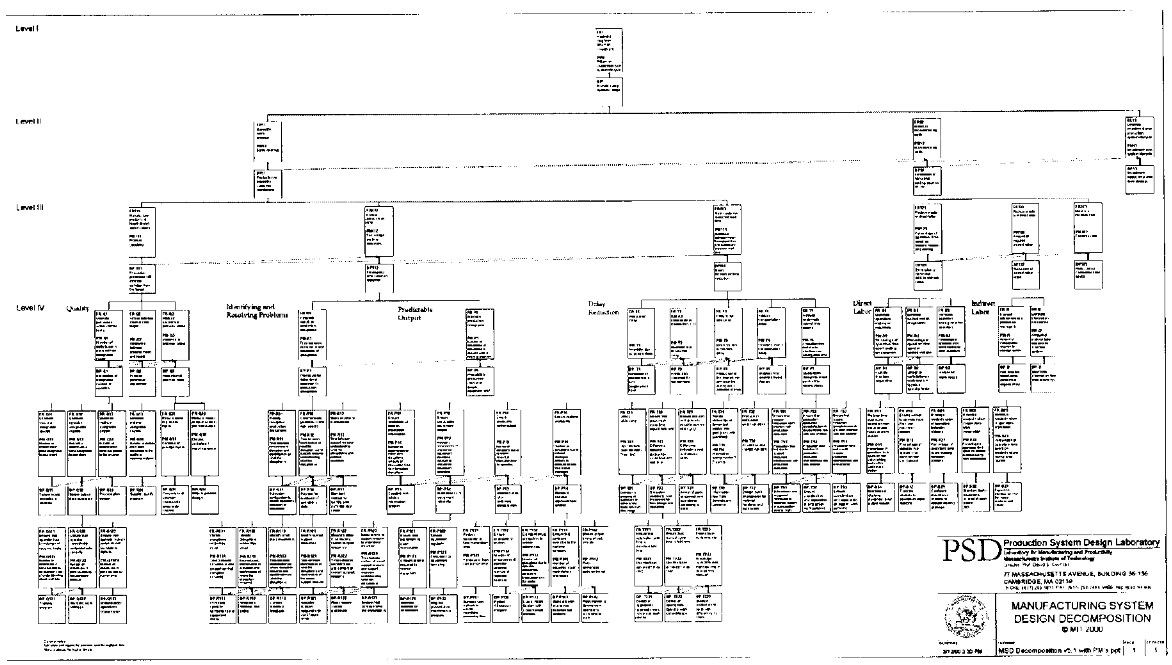


Figure 4.1: Manufacturing System Design (MSD) Decomposition

This chapter will discuss the performance measurements for the high level FRs (Levels 1 through 3) of the MSD Decomposition. Then, the PMs for each branch (Quality, Identifying & Resolving Problems, Predictable Output, Delay Reduction, Direct Labor, and Indirect Labor) will be discussed individually.

Although performance measurements have been associated with each and every FR of the MSD Decomposition, some metrics may provide more useful information than others.

Some metrics may be too general in scope to provide useful information about the manufacturing system's performance whereas other metrics may be too specific in scope to be applicable to a particular manufacturing system being measured. For example, the highest level PM is 'Return on investment,' which in most cases is too general to provide information which can be used to improve the manufacturing system's performance. In addition, some metrics may be quite simple and straightforward to measure while others may be nearly impossible to measure. Because of this wide range of possibilities, it may be useful to pinpoint a few key performance measurements which are both useful and straightforward to measure.

4.2 High Level Performance Measurements of the MSDD

4.2.1 Level 1 Performance Measurement

Level 1 (the highest level) of the MSD Decomposition is FR1. PM1 has been defined for FR1 as shown in Figure 4.2.

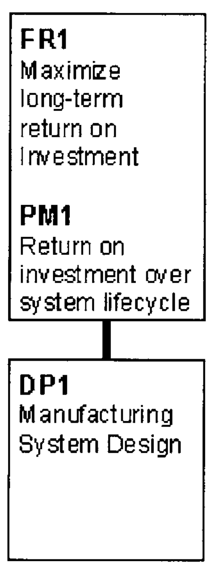


Figure 4.2: Level 1 Performance Measurement

FR1: Maximize long-term return on investment

PM1: Return on investment over system lifecycle

PM1 is a very straightforward metric for FR1. This is a financial measure which will provide information about the profitability of the manufacturing system at the highest enterprise objective level. The goal is to maximize the return on investment. The decomposition of FR1 will outline how this goal can be achieved with a manufacturing system design.

4.2.2 Level 2 Performance Measurements

Level 2 of the MSD Decomposition is FRs 11, 12, and 13. PMs 11, 12, and 13 have been defined for FRs 11, 12, and 13, respectively, as shown in Figure 4.3.

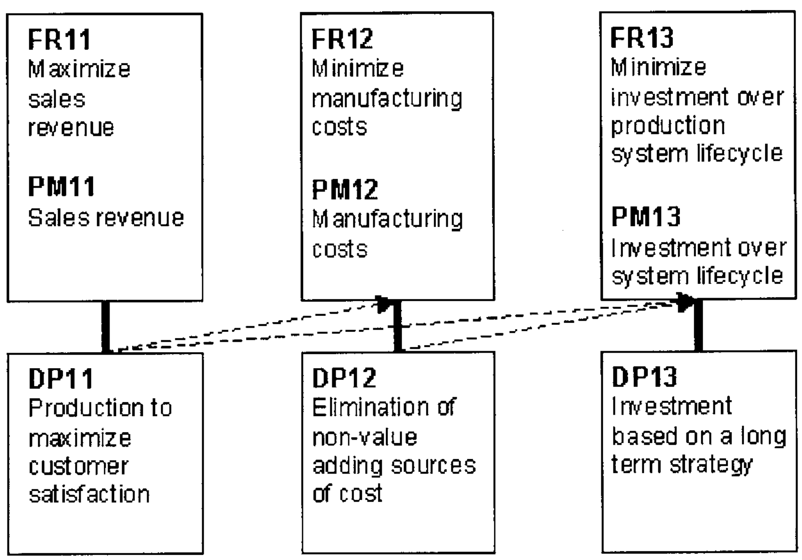


Figure 4.3: Level 2 Performance Measurements

FR11: Maximize sales revenue

PM11: Sales revenue

FR12: Minimize manufacturing costs

PM12: Manufacturing costs

FR13: Minimize investment over production system lifecycle

PM13: Investment over system lifecycle

The Level 2 PMs are also straightforward metrics for the FRs. These metrics are derived from the equation for return on investment shown in Equation 4.1.

$$\text{Return on Investment} = \frac{\text{Sales Revenue - Manufacturing Costs}}{\text{Investment}} \quad \text{(Eq. 4.1)}$$

Manufacturing costs are the sum of all operating costs including materials, direct labor, indirect labor, and overhead. Investment includes the costs of designing and implementing a manufacturing system, capital equipment, and others which are not associated with the actual operation of the system. The goal is to maximize sales revenue while minimizing both manufacturing costs and investment such that return on investment will be maximized. In this way, the Level 2 PMs support the Level 1 PM.

4.2.3 Level 3 Performance Measurements

Level 3 of the MSD Decomposition is FRs 111, 112, 113 and FRs 121, 122, and 123. PMs 111, 112, 113 and PMs 121, 122, and 123 have been defined for the above FRs, respectively, as shown in Figure 4.4.

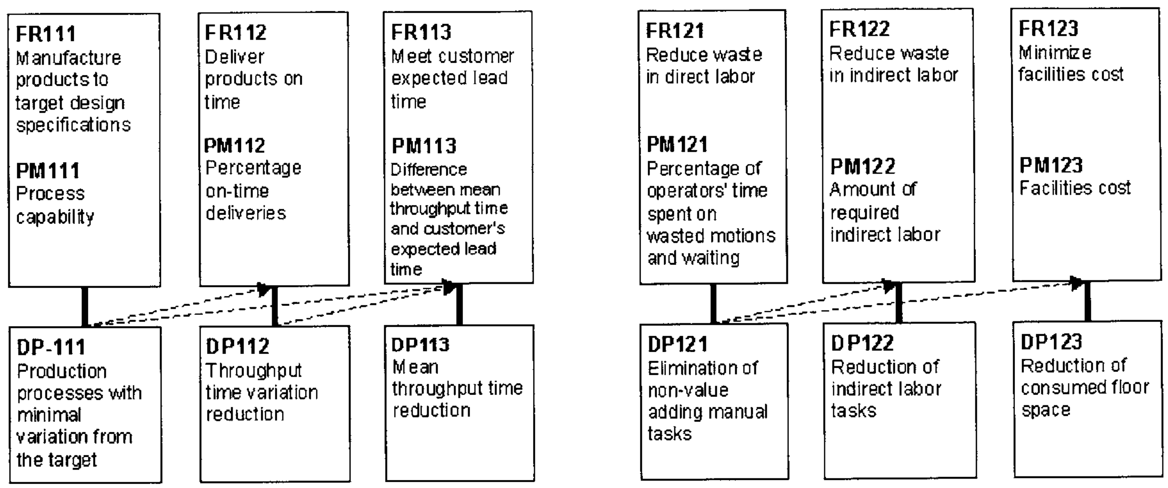


Figure 4.4: Level 3 Performance Measurements

The Level 3 PMs concerned with maximizing sales revenue measure the overall quality of the manufacturing processes, and the mean and variability of the throughput time of the manufacturing system. The Level 3 PMs concerned with minimizing manufacturing costs measure the wastes in direct labor, the wastes in indirect labor, and the cost of facilities.

FR111: Manufacture products to target design specifications
PM111: Process capability

FR112: Deliver products on time
PM112: Percentage on-time deliveries

FR113: Meet customer expected lead time
PM113: Difference between mean throughput time and customer's expected lead time

PM111 measures the process capability for the processes in the manufacturing system, which will lead to minimizing variation, σ_p, in the quality of the manufacturing processes. PM112 measures the percent of on-time deliveries to the customer, which will lead to minimizing variation, σ_X, in the throughput time of the manufacturing system. PM113 measures the difference between the mean throughput time of the manufacturing system and the customer expected lead time, which will lead to matching the mean throughput time of the system to the customer expected lead time. These three PMs together, illustrated in Figure 4.5, will help to maximize sales revenue by maximizing customer satisfaction through higher product quality and more predictable throughput times.

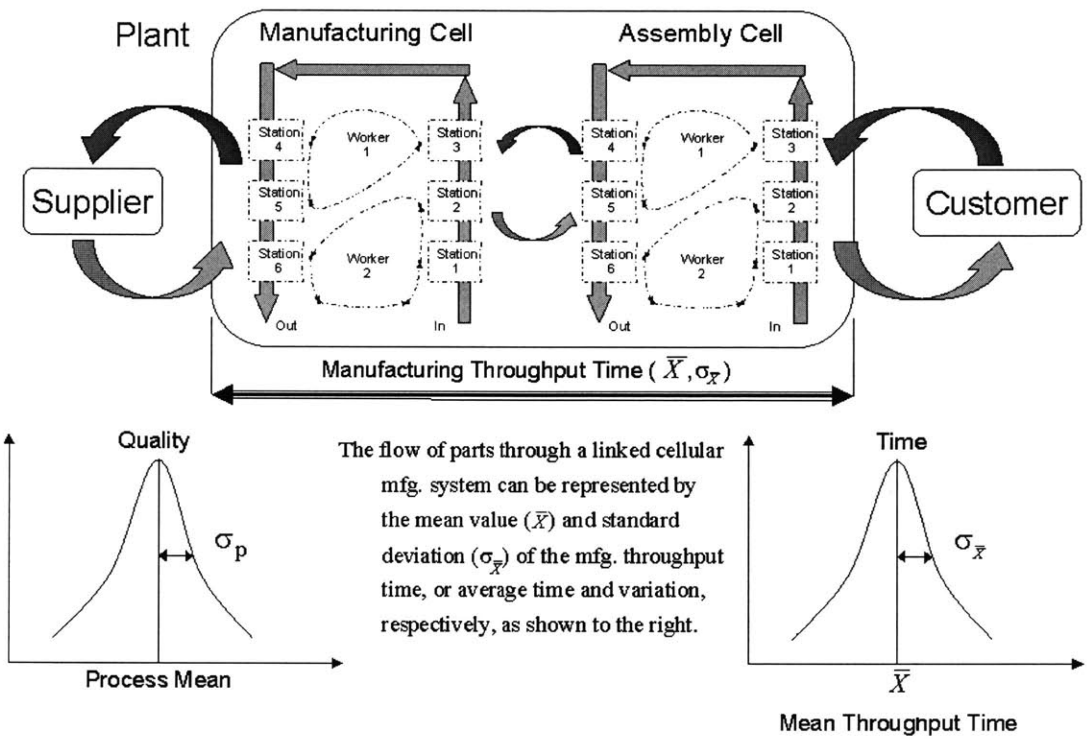


Figure 4.5: Level 3 Performance Measurements for Variation in Quality, and Mean and Variation in Throughput Time

FR121: Reduce waste in direct labor

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

FR122: Reduce waste in indirect labor

PM122: Amount of required indirect labor

FR123: Minimize facilities cost

PM123: Facilities cost

PM121 measures the percentage of operators' time that is wasted, which will lead to minimizing all types of wasteful motions and tasks. PM122 measures the amount of indirect labor required in the manufacturing system, which will lead to reducing the amount of unnecessary indirect labor tasks so that the system operates more effectively with fewer control efforts. PM123 measures the cost of facilities for the manufacturing system, which will lead to reducing wasted floorspace and other costs associated with that waste. These three PMs together will help to minimize manufacturing costs by eliminating non-value-adding sources of cost in the entire manufacturing system.

4.3 Lower Level Performance Measurements of the MSDD

4.3.1 Quality Branch Performance Measurements

The Quality branch of the MSD Decomposition spans levels 4 through 6. PMs have been defined for each of the FRs in this branch, as shown in Figure 4.6.

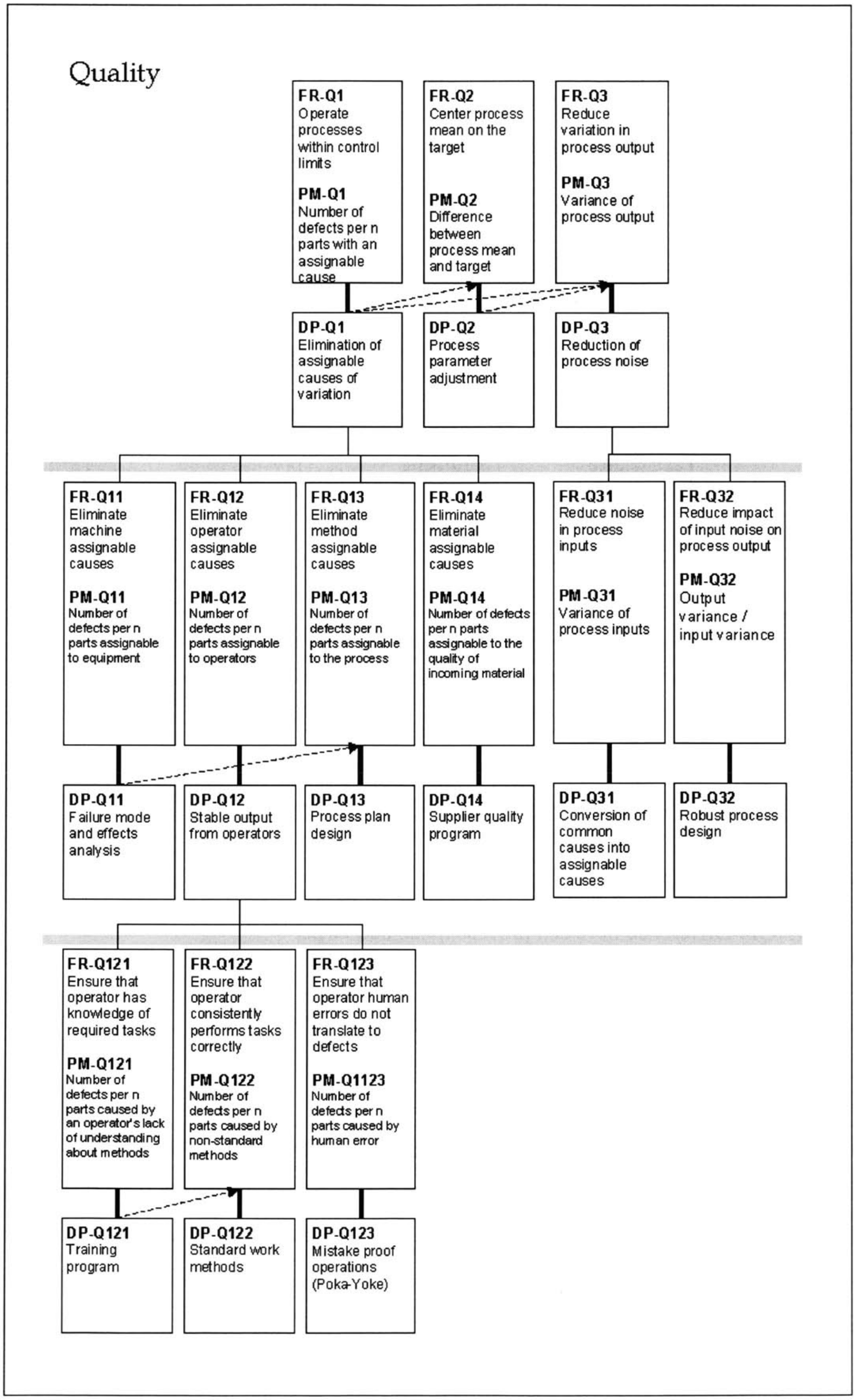


Figure 4.6: Quality Branch of the MSD Decomposition

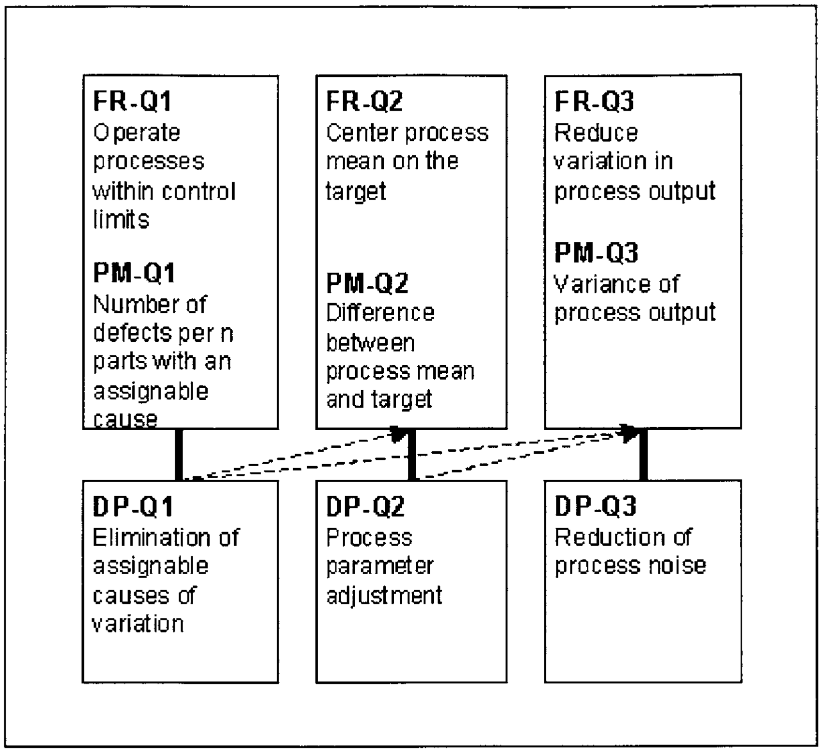


Figure 4.7: Top Level of the Quality Branch of the MSD Decomposition

FR-Q1: Operate processes within control limits

PM-Q1: Number 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

The PMs for the Quality branch measure three different aspects of the quality of processes, and the top level is shown in Figure 4.7. PM-Q1 measures the number of defects which are assignable to specific causes. PM-Q2 measures the difference between the actual mean of a process and the desired target mean for the process. PM-Q3 measures the total variation in the output of a process. Using these three measures, the total quality of a process can be determined so that improvements can be made where needed.

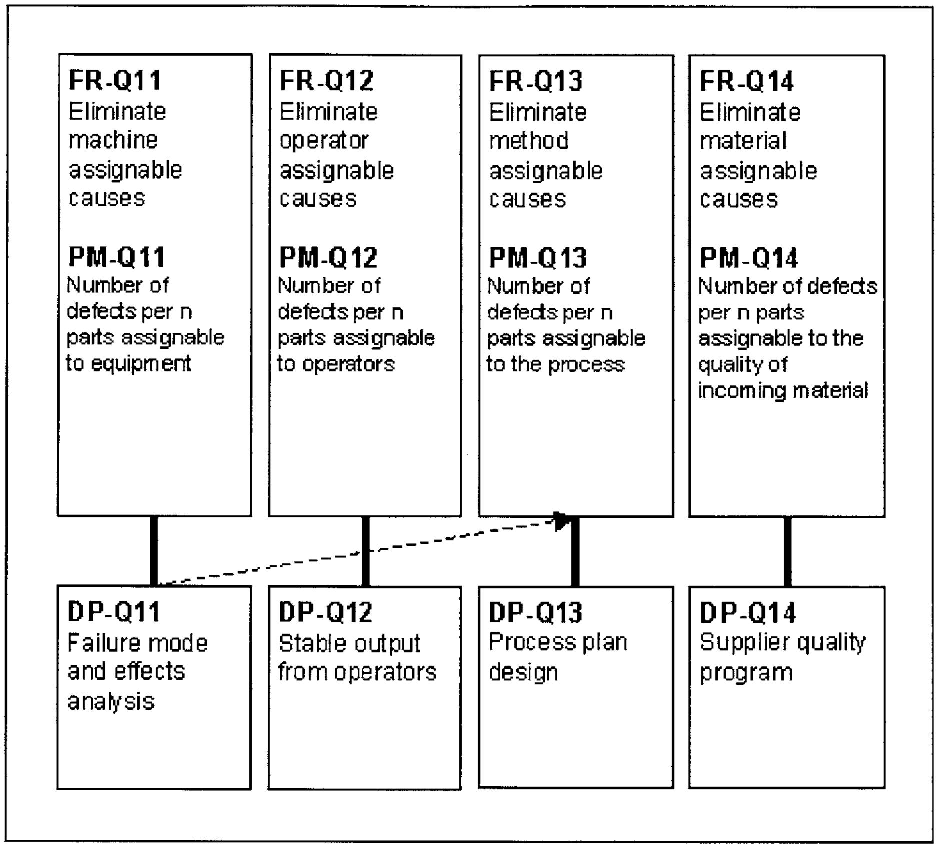


Figure 4.8: Middle Level of the Quality Branch of the MSD Decomposition

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 process

FR-Q14: Eliminate material assignable causes

PM-Q14: Number of defects per n parts assignable to the quality of incoming material

PMs-Q11, Q12, Q13, and Q14 shown in Figure 4.8 measure the number of defects which are assignable to equipment, operators, processes, and incoming materials, respectively, as shown in Figure 4.9. These performance metrics provide more specific information about the causes of defects and can be very useful in eliminating the root causes so that the total number of defects is continually reduced.

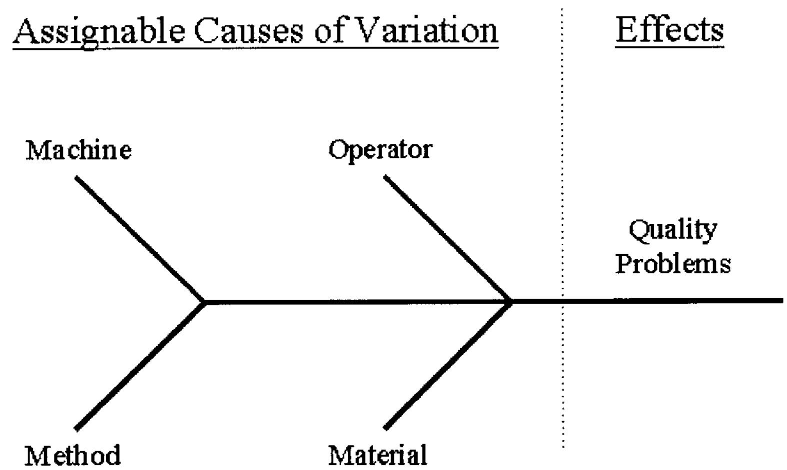


Figure 4.9: Fishbone Diagram of the Assignable Causes of Quality Problems

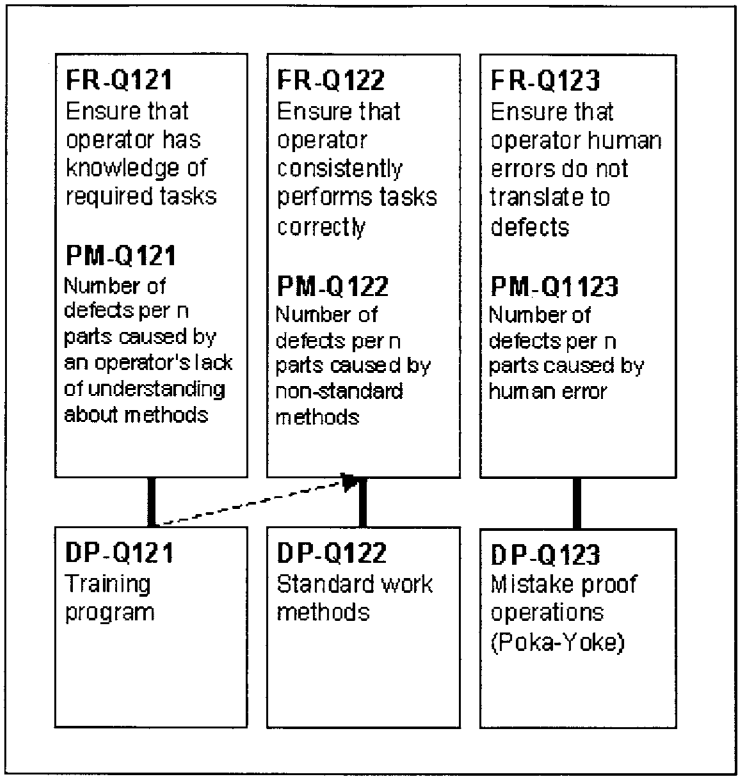


Figure 4.10: Lower Level of the Quality Branch of the MSD Decomposition

FR-Q121: Ensure that operator has knowledge of required tasks

PM-Q121: Number of defects per n parts caused by an operator's lack of understanding about methods

FR-Q122: Ensure that operator consistently performs tasks correctly

PM-Q122: Number of defects per n parts caused by non-standard methods

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

PM-Q123: Number of defects per n parts caused by human error

PMs-Q121, Q122, and Q123 shown in Figure 4.10 provide more specific metrics about causes of defects assignable to operators. These PMs measure the number of defects caused by lack of knowledge or appropriate training, by non-standard work methods, and by simple human errors, respectively. In order to reduce the number of defects caused by the operators, they must be well-trained to follow standard work methods and procedures.

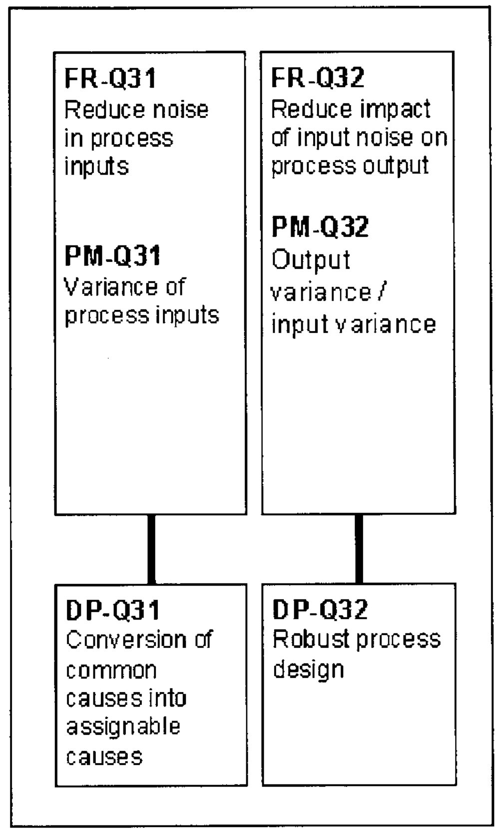


Figure 4.11: Middle Level of the Quality Branch of the MSD Decomposition

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

PM-Q31 measures the variation of the inputs to a process, and PM-Q32 measures the ratio of the output variation to the input variation for a process as shown in Figure 4.11. By measuring the variation of the inputs to a process, this variation can be reduced to provide more stable inputs to a process. By measuring the ratio of output variation to input variation for a process, it can be determined whether the process adds additional variation or eliminates some of the input variation. If a certain level of input variation must be tolerated, then the process should be made robust in order to reduce the final output variation.

4.3.2 Identifying and Resolving Problems Branch Performance Measurements

The Identifying and Resolving Problems branch of the MSD Decomposition spans levels 4 through 6. PMs have been defined for each of the FRs in this branch, as shown in Figure 4.12.

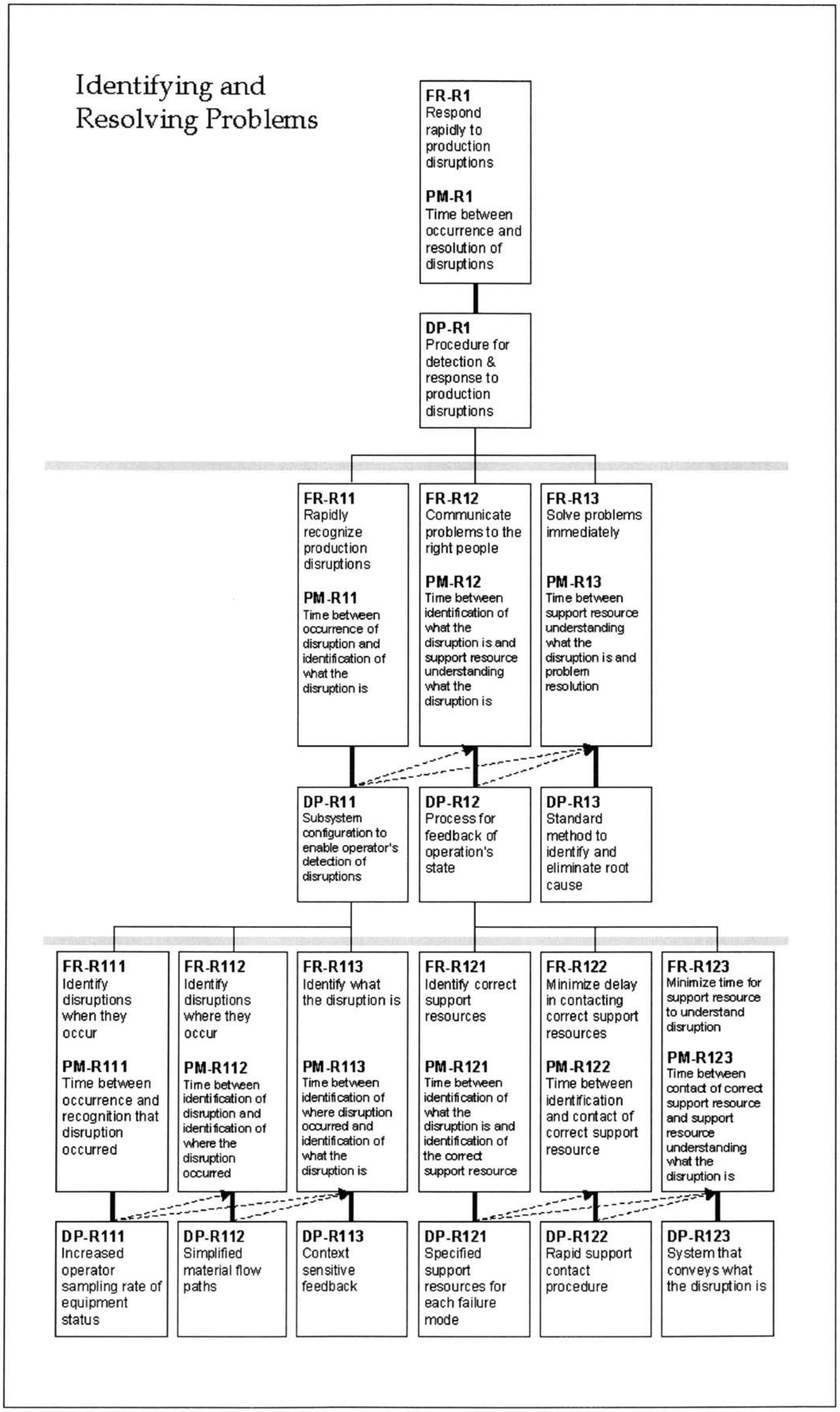


Figure 4.12: Identifying and Resolving Problems Branch of the MSD Decomposition

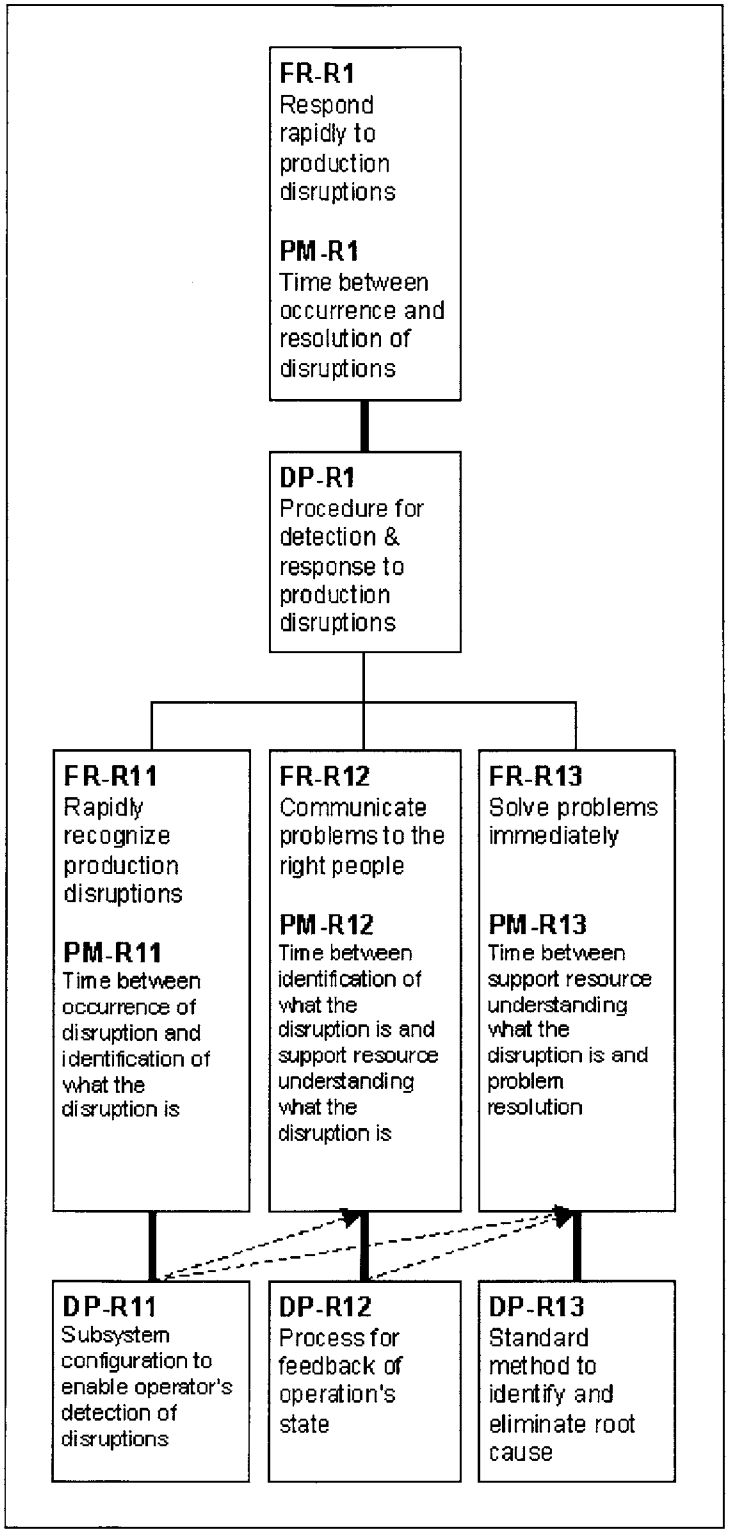


Figure 4.13: Top Levels of the Identifying and Resolving Problems Branch of the MSD Decomposition

FR-R1: Respond rapidly to production disruptions

PM-R1: Time between occurrence and resolution of disruptions

FR-R11: Rapidly recognize production disruptions

PM-R11: Time between occurrence of disruption and identification of what the disruption is

FR-R12: Communicate problems to the right people

PM-R12: Time between identification of what the disruption is and support resource understanding what the disruption is

FR-R13: Solve problems immediately

PM-R13: Time between support resource understanding what the disruption is and problem resolution

The PMs for the Identifying and Resolving Problems branch shown in Figure 4.13 measure various segments of time between the occurrence of a disruption and its final resolution. PM-R1 is the aggregate time between occurrence and resolution of a disruption. PMs-R11, R12, and R13 divide the total time of PM-R1 into three segments as shown in Figure 4.14. PM-R11 measures the time between disruption occurrence and identification. PM-R12 measures the time between disruption identification and support resource understanding the reason(s) for the disruption. PM-R13 measures the time between the support resource understanding the disruption and the final resolution of the disruption.

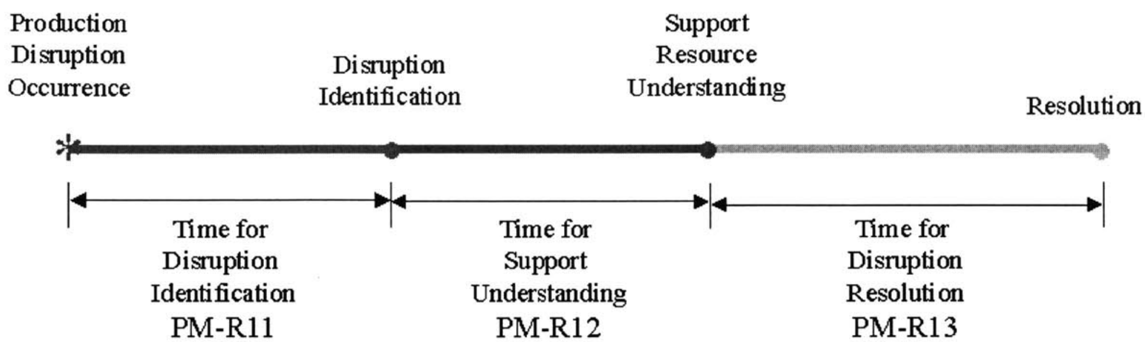


Figure 4.14: Time Segments Between Disruption Occurrence and Final Resolution

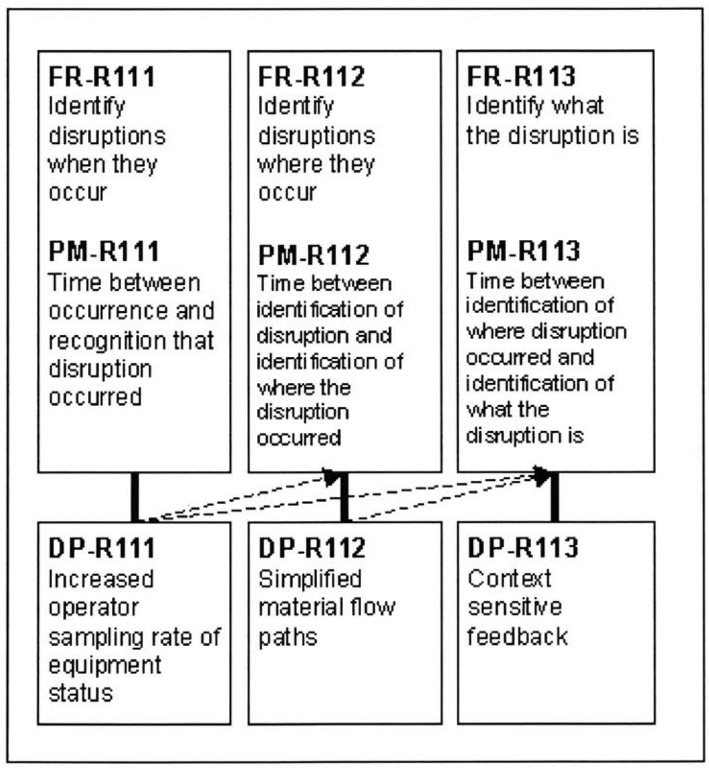


Figure 4.15: Lower Level of the Identifying and Resolving Problems Branch of the MSD Decomposition

FR-R111: Identify disruptions when they occur

PM-R111: Time between occurrence and recognition that disruption occurred

FR-R112: Identify disruptions where they occur

PM-R112: Time between identification of disruption and identification of where the disruption occurred

FR-R113: Identify what the disruption is

PM-R113: Time between identification of where disruption occurred and identification of what the disruption is

PMs-R111, R112, and R113 shown in Figure 4.15 further separate PM-R11 into three more specific time segments. These three time segments are shown in Figure 4.16. PM-R111 measures the time between disruption occurrence and awareness of the disruption. PM-R112 measures the time between awareness of the disruption and knowledge of the location of the disruption occurrence. PM-R113 measures the time between location of the disruption occurrence and identification of what the disruption is.

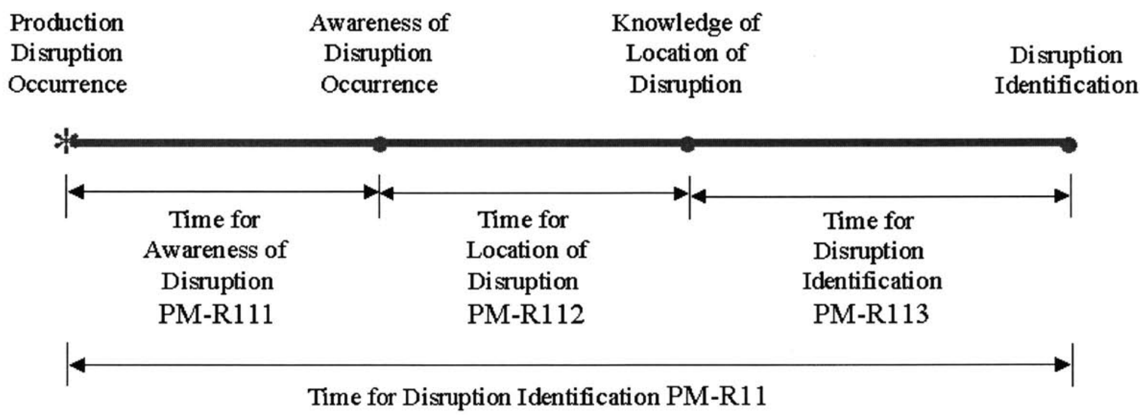


Figure 4.16: Time Segments Between Disruption Occurrence and Disruption Identification

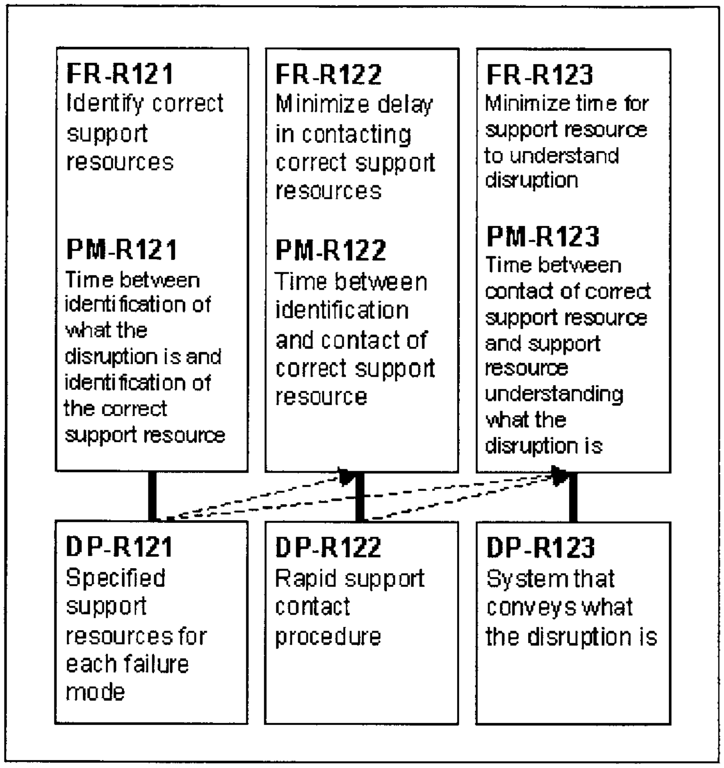


Figure 4.17: Lower Level of the Identifying and Resolving Problems Branch of the MSD Decomposition

FR-R121: Identify correct support resources

PM-R121: Time between identification of what the disruption is and identification of the correct support resource

FR-R122: Minimize delay in contacting correct support resources

PM-R122: Time between identification and contact of correct support resource

FR-R123: Minimize time for support resource to understand disruption

PM-R123: Time between contact of correct support resource and support resource understanding what the disruption is

PMs-R121, R122, and R123 shown in Figure 4.17 further subdivide PM-R12 into three more specific time segments. These three time segments follow immediately after the time segments in Figure 4.16 and are shown in Figure 4.18. PM-R121 measures the time between identification of the disruption and identification of the correct support resource to resolve the disruption. PM-R122 measures the time between identification of the correct support resource and actual contact with that resource. PM-R123 measures the time between contact with the support resource and the support resource understanding the reason(s) for the disruption.

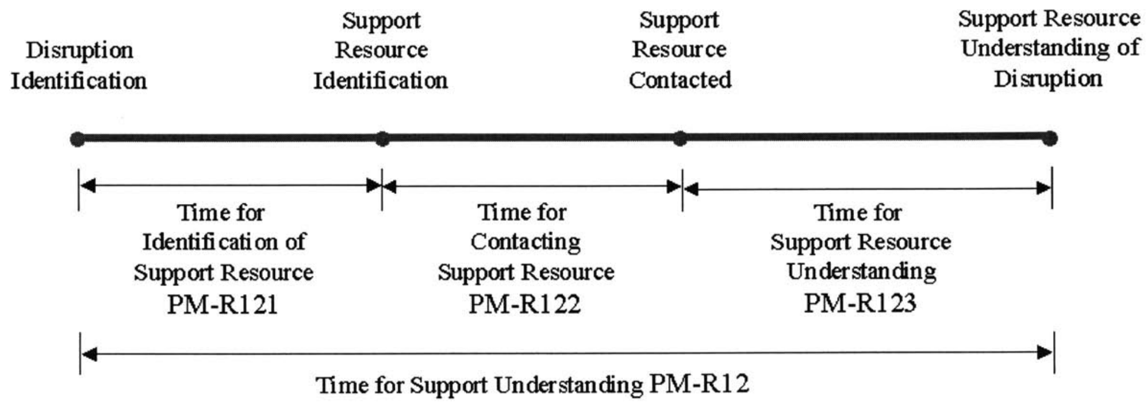


Figure 4.18: Time Segments Between Disruption Identification and Support Resource Understanding

Measuring all of the above time segments will help to pinpoint which areas are in need of the most improvement. For example, the time between disruption occurrence and awareness of the disruption may be very long, which may mean that the operators cannot quickly detect errors when they occur. Or, the time between identification of the correct support resource and actual contact of that resource may be very long, which may mean that the organizational structure of the manufacturing system is too complicated and prevents quick reaction to disruptions. The goal of measuring all of the above time segments between a disruption occurrence and its final resolution is to decrease the length of time for each of the segments to an absolute minimum such that the manufacturing system responds rapidly and effectively to resolve disruptions.

4.3.3 Predictable Output Branch Performance Measurements

The Predictable Output branch of the MSD Decomposition spans levels 4 through 6. PMs have been defined for each of the FRs in this branch, as shown in Figure 4.19.

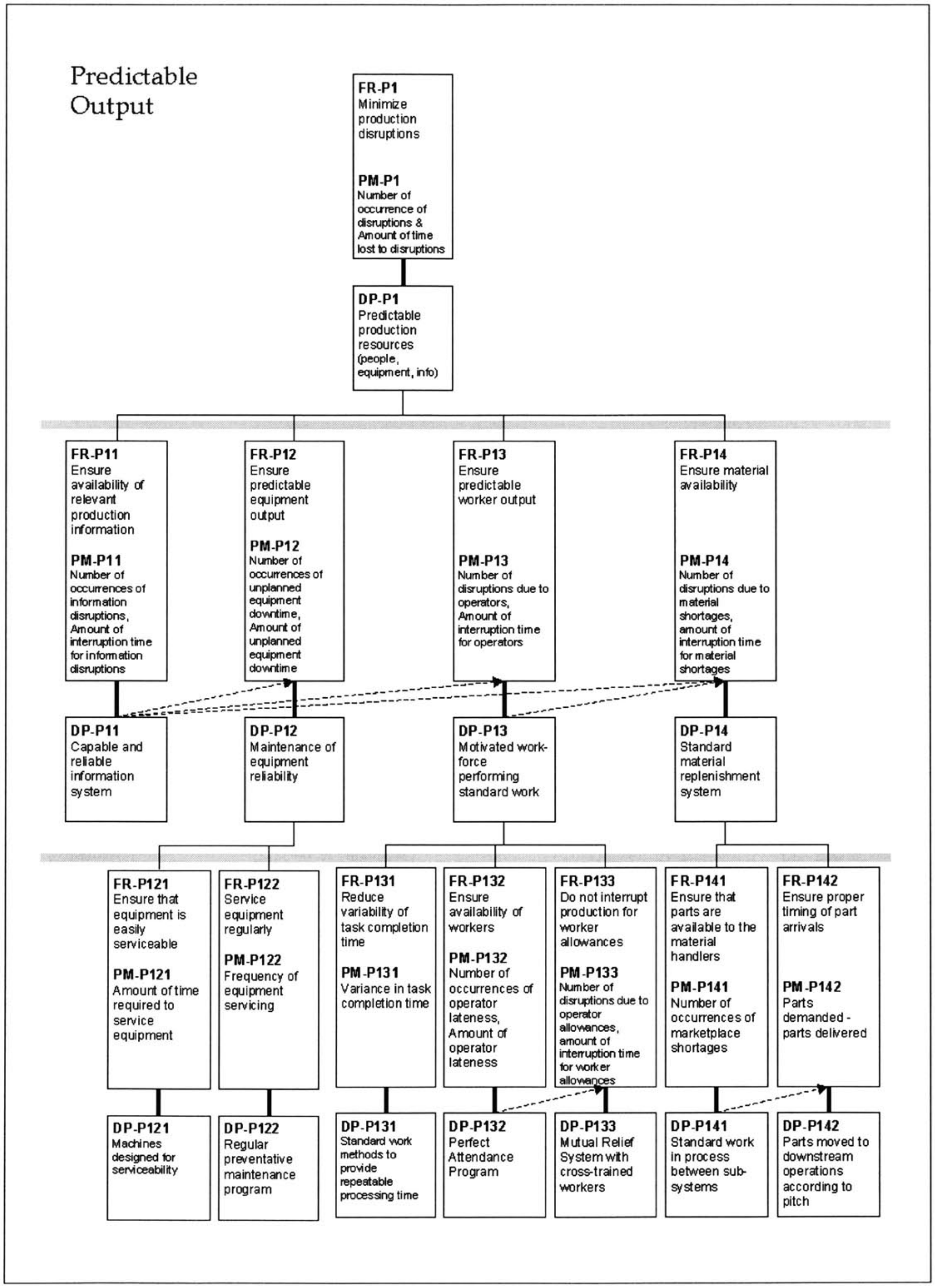


Figure 4.19: Predictable Output Branch of the MSD Decomposition

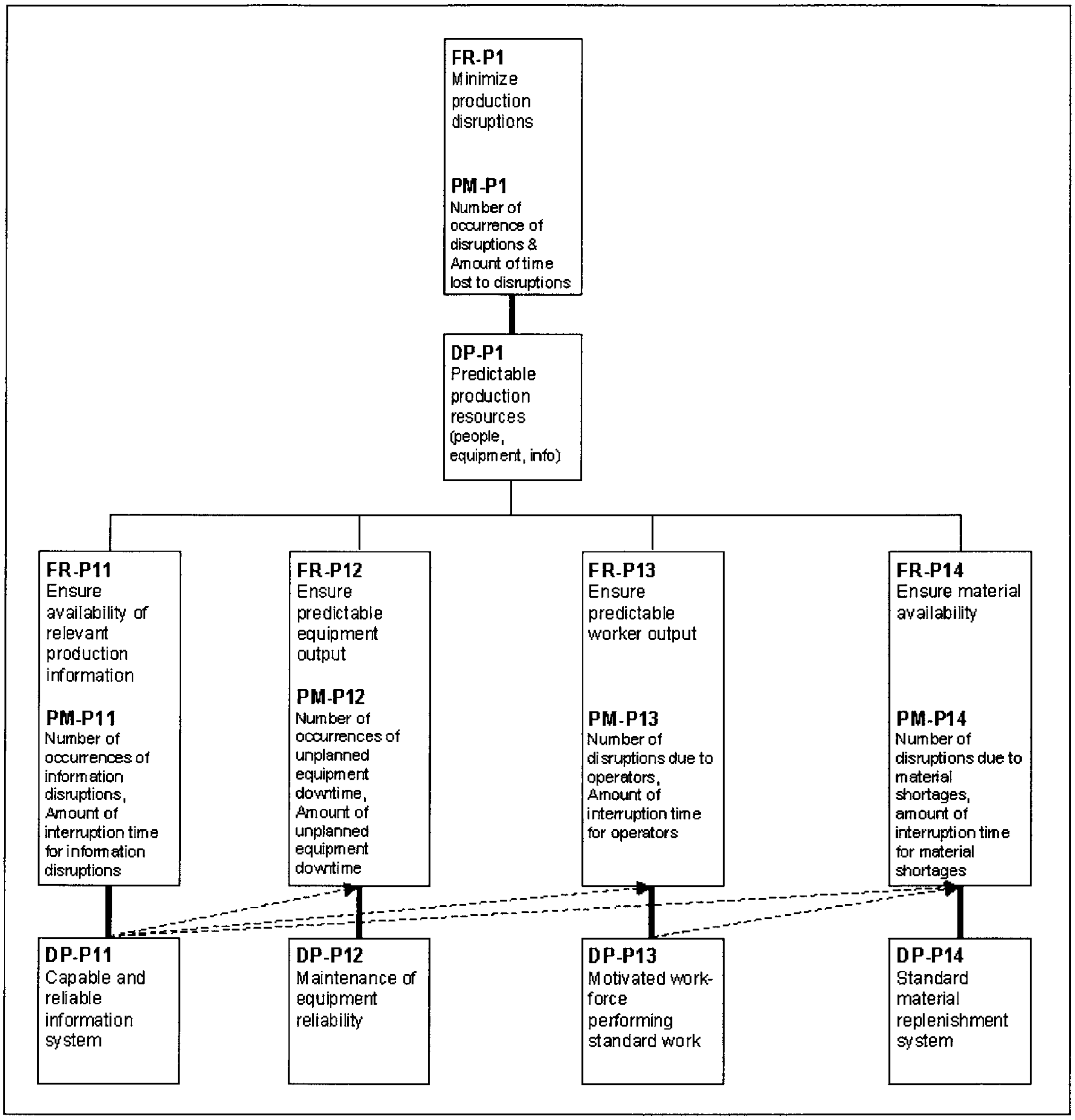


Figure 4.20: Top Levels of the Predictable Output Branch of the MSD Decomposition

FR-P1: Minimize production disruptions

PM-P1: Number of occurrences of disruptions & amount of time lost to disruptions

FR-P11: Ensure availability of relevant production information

PM-P11: Number of occurrences of information disruptions, amount of interruption time for information disruptions

FR-P12: Ensure predictable equipment output

PM-P12: Number of occurrences of unplanned equipment downtime, amount of unplanned equipment downtime

FR-P13: Ensure predictable worker output

PM-P13: Number of disruptions due to operators, amount of interruption time for operators

FR-P14: Ensure material availability

PM-P14: Number of disruptions due to material shortages, amount of interruption time for material shortages

The PMs for the Predictable Output branch shown in Figure 4.20 measure, in general, the number of occurrences of disruptions and the amount of time lost due to those disruptions. PM-P1 measures the total number of disruptions and the resultant time lost due to all types of assignable causes. PMs-P11, P12, P13, and P14 each measure the number of disruptions and time lost due to four assignable causes: information, equipment, operators, and materials, respectively. These four causes are shown graphically in Figure 4.21 very similar to Figure 4.9.

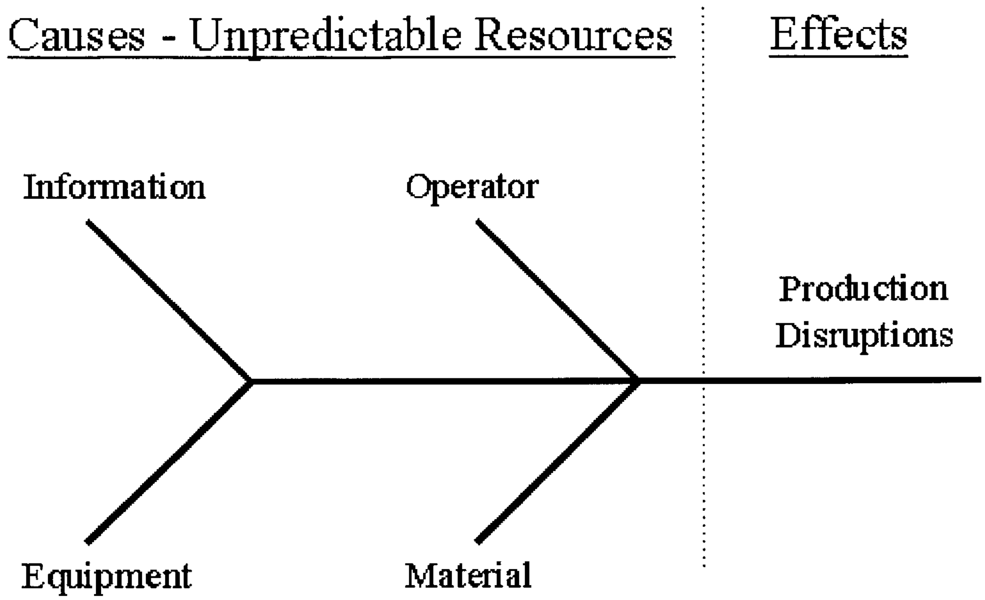


Figure 4.21: Fishbone Diagram of the Assignable Causes of Production Disruptions

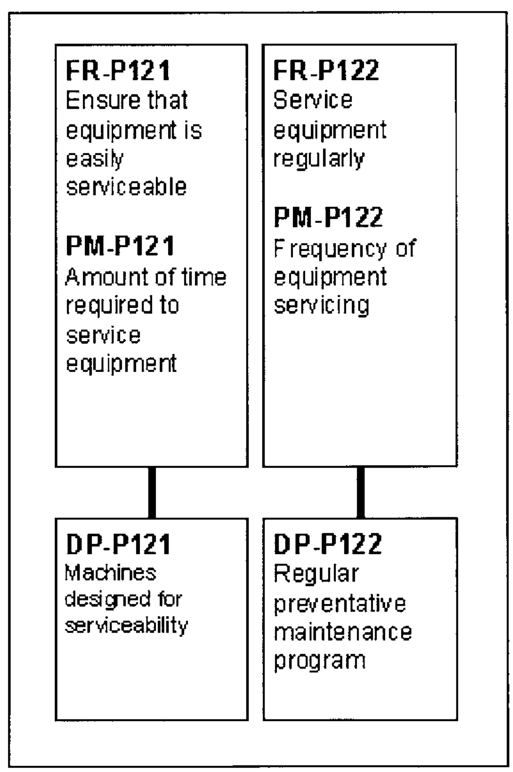


Figure 4.22: Lower Level of the Predictable Output Branch of the MSD Decomposition

FR-P121: Ensure that equipment is easily serviceable

PM-P121: Amount of time required to service equipment

FR-P122: Service equipment regularly

PM-P122: Frequency of equipment servicing

The remaining PMs of this branch are more specific metrics for equipment predictability, operator predictability, and material availability. PMs-P121 and P122 are shown in Figure 4.22. PM-P121 measures the amount of time required to service equipment so that this time can be reduced. PM-P122 measures the frequency with which the equipment requires service so that the reliability of the equipment can be assessed and improved.

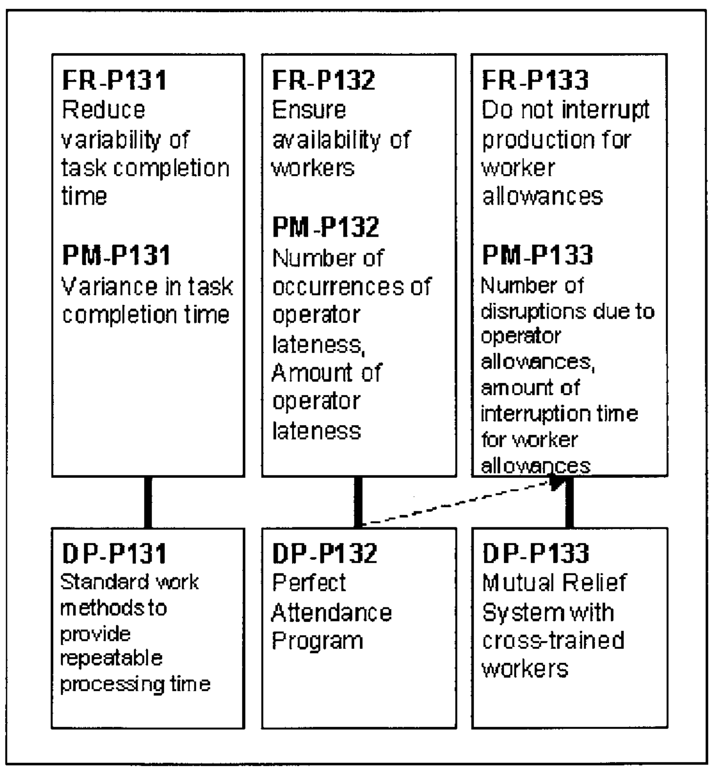


Figure 4.23: Lower Level of the Predictable Output Branch of the MSD Decomposition

FR-P131: Reduce variability of task completion time

PM-P131: Variance in task completion time

FR-P132: Ensure availability of workers

PM-P132: Number of occurrences of operator lateness, amount of operator lateness

FR-P133: Do not interrupt production for worker allowances

PM-P133: Number of disruptions due to operator allowances, amount of interruption time for worker allowances

PMs-P131, P132, and P133 are shown in Figure 4.23. PM-P131 measures the variation in the operators' task completion times in order to achieve consistent times with little variation. PMs-P132 and P133 measure the number of disruptions and the resultant time lost due to operator absenteeism and operator allowances in order to foster more responsible operators.

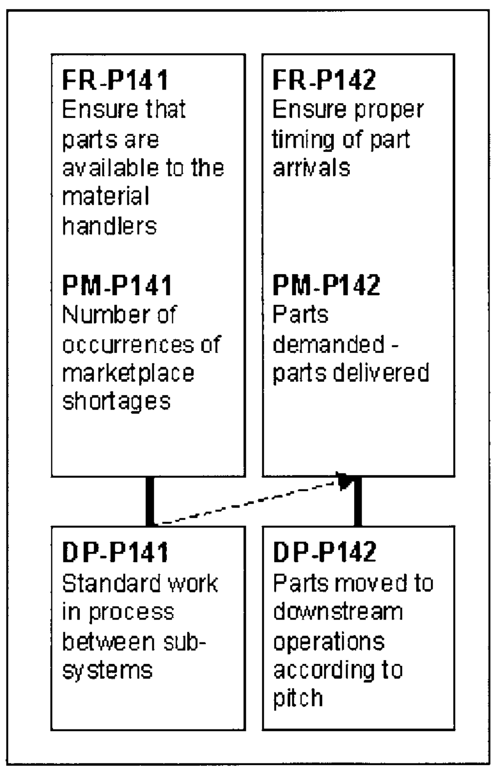


Figure 4.24: Lower Level of the Predictable Output Branch of the MSD Decomposition

FR-P141: Ensure that parts are available to the material handlers

PM-P141: Number of occurrences of marketplace shortages

FR-P142: Ensure proper timing of part arrivals

PM-P142: Parts demanded – parts delivered

PMs-P141 and P142 are shown in Figure 4.24. PM-P141 measures the number of occurrences of marketplace shortages in order to prevent starvation of the manufacturing system. PM-P142 measures the difference between the number of parts demanded by the manufacturing system and the actual number of parts delivered in order to provide more information about parts' unavailability when they are needed.

4.3.4 Delay Reduction Branch Performance Measurements

The Delay Reduction branch of the MSD Decomposition spans levels 4 through 6. PMs have been defined for each of the FRs in this branch, as shown in Figure 4.25.

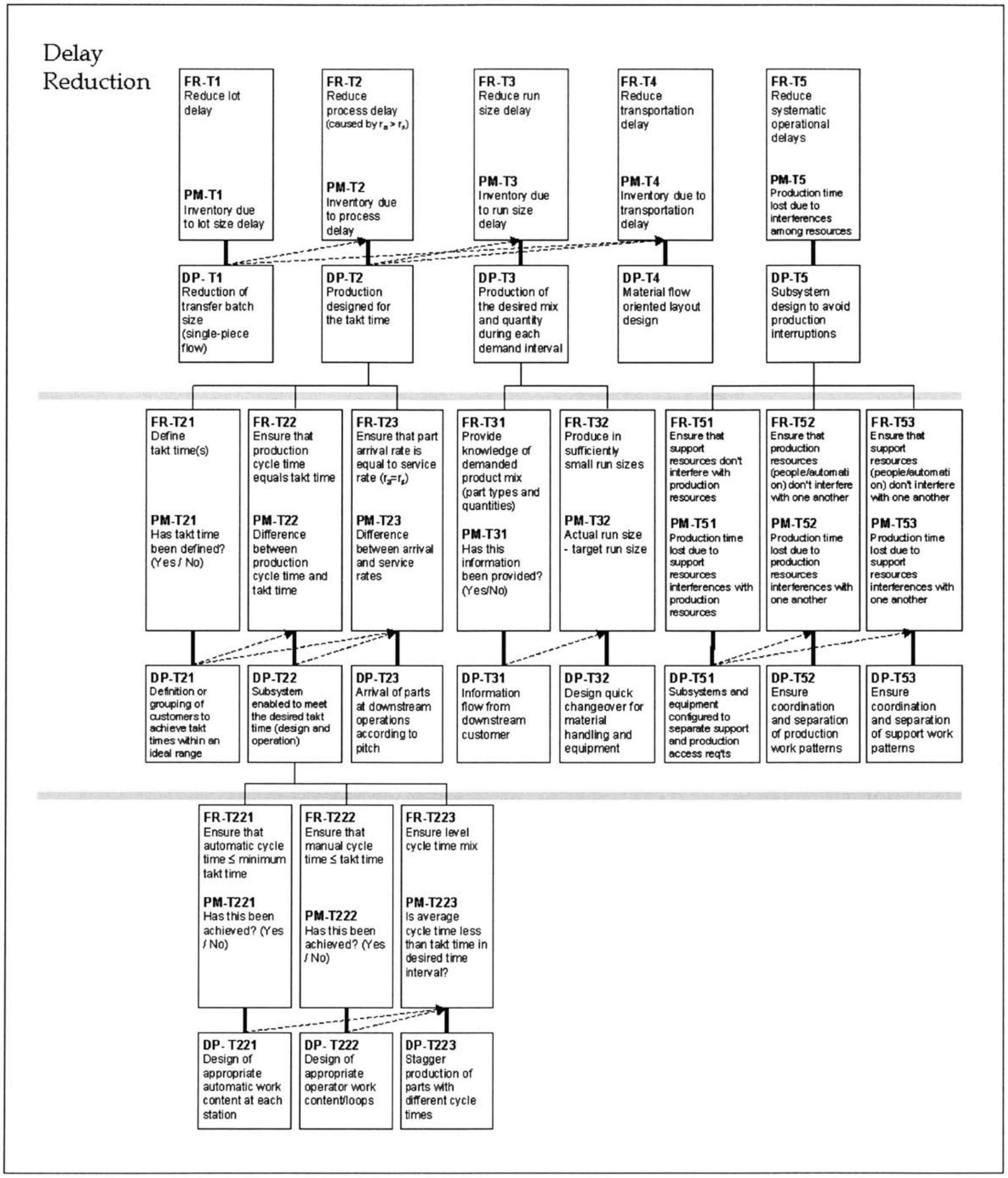


Figure 4.25: Delay Reduction Branch of the MSD Decomposition

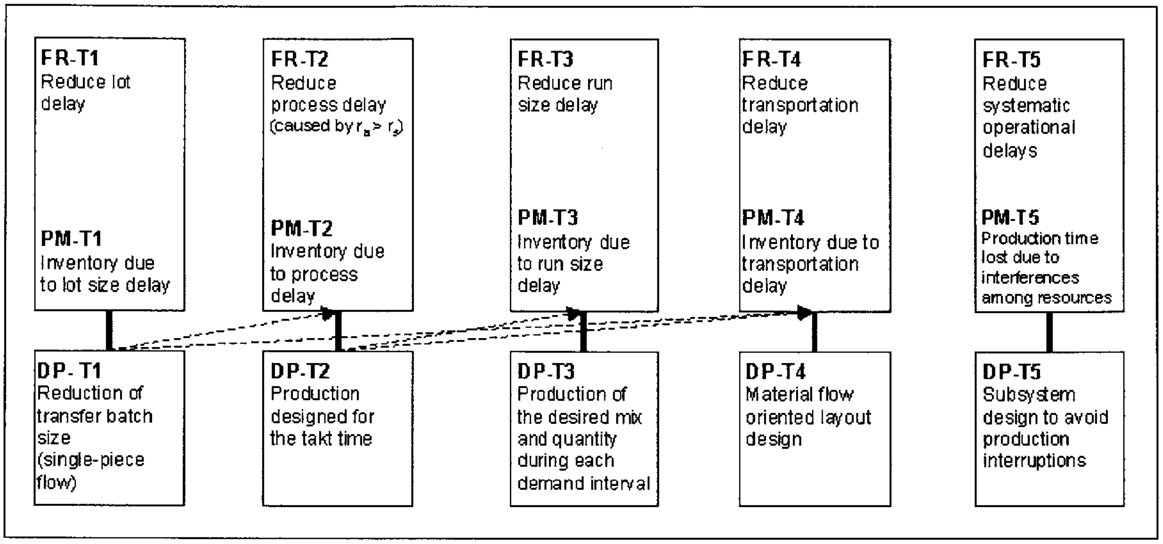


Figure 4.26: Top Level of the Delay Reduction Branch of the MSD Decomposition

FR-T1: Reduce lot delay

PM-T1: Inventory due to lot size delay

FR-T2: Reduce process delay

PM-T2: Inventory due to process delay

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: Production time lost due to interferences among resources

The PMs for the first level of the Delay Reduction branch shown in Figure 4.26 measure, in general, the levels of inventory created by each of the five types of delays. PM-T1 measures the inventory created by lot delay, which can be reduced by decreasing the lot sizes in manufacturing. PM-T2 measures the inventory created by process delay, which can be reduced by balancing all the operations of a manufacturing system to takt time. PM-T3 measures the inventory created by run size delay, which can be reduced by leveling the mix of production with smaller run sizes of each part type. PM-T4 measures the inventory created by transportation delay, which can be reduced by designing the manufacturing system layout to minimize the distance that parts must travel. PM-T5 measures the production time lost due to systematic operational delays, which can be reduced by defining the work for both production and support resources to prevent interferences.

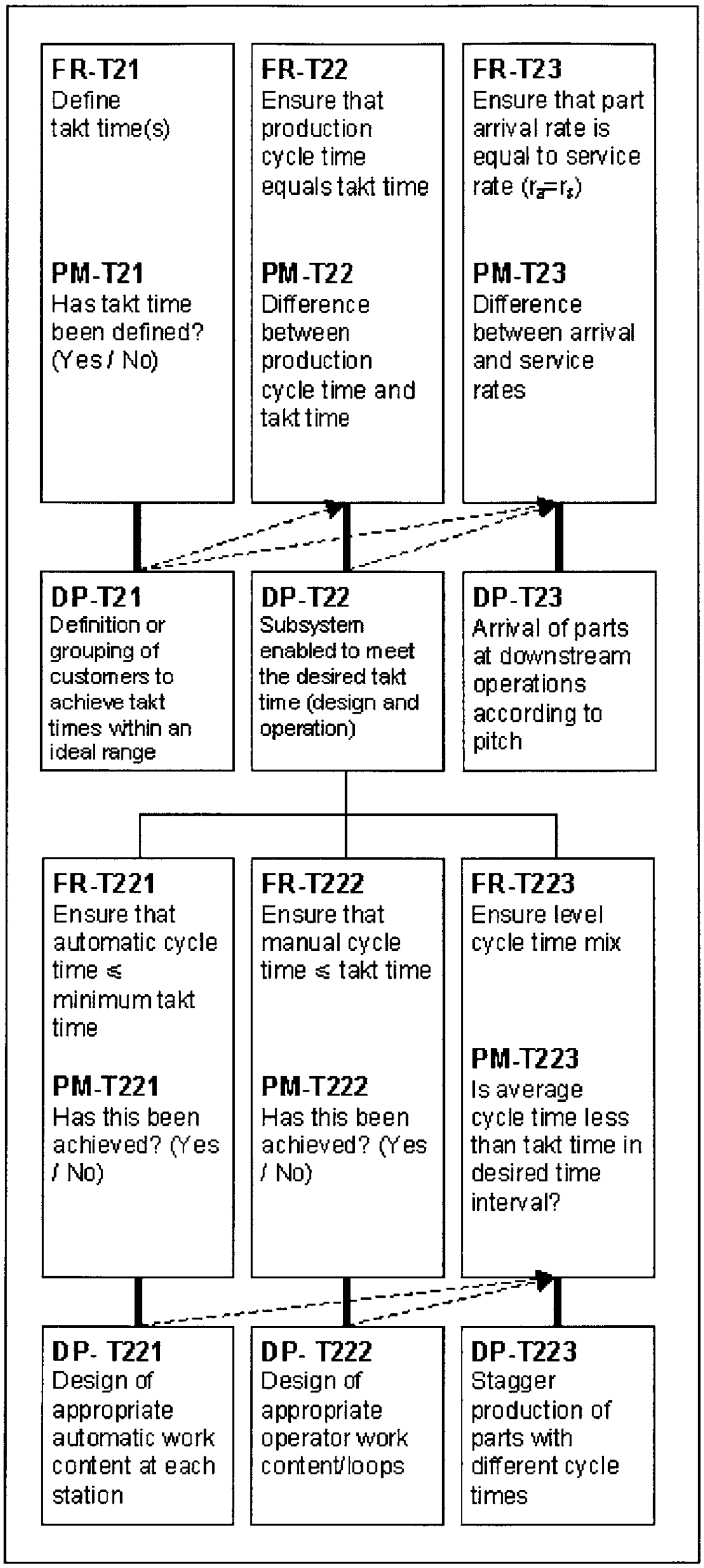


Figure 4.27: Middle/Lower Levels of the Delay Reduction Branch of the MSD Decomposition

FR-T21: Define takt time(s)
PM-T21: Has takt time been defined? (Y/N)

FR-T22: Ensure that production cycle time equals takt time
PM-T22: Difference between production cycle time and takt time

FR-T23: Ensure that part arrival rate is equal to service rate
PM-T23: Difference between arrival and service rates

FR-T221: Ensure that automatic cycle time ≤ minimum takt time
PM-T221: Has this been achieved? (Y/N)

FR-T222: Ensure that manual cycle time ≤ takt time
PM-T222: Has this been achieved? (Y/N)

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

The PMs shown in Figure 4.27 which extend from PM-T2 (process delay) ensure that all aspects of the manufacturing system are balanced to the defined takt time. PM-T21 requires that the manufacturing system have a defined takt time. PM-T22 measures the difference between the production cycle time and the takt time so that production will be able to meet customer demand. PM-T23 measures the difference between part arrival rate and service rate so that all parts will be available when they are needed. PM-T221 requires that the automatic cycle times of equipment be less than or equal to the takt time so that equipment will not slow down production. PM-T222 requires that the manual cycle times of operators be less than or equal to the takt time so that operators will not slow down production. PM-T223 requires that the average cycle time of all the processes in the manufacturing system be less than or equal to the takt time so that the system, as a whole, is able to meet customer demand.

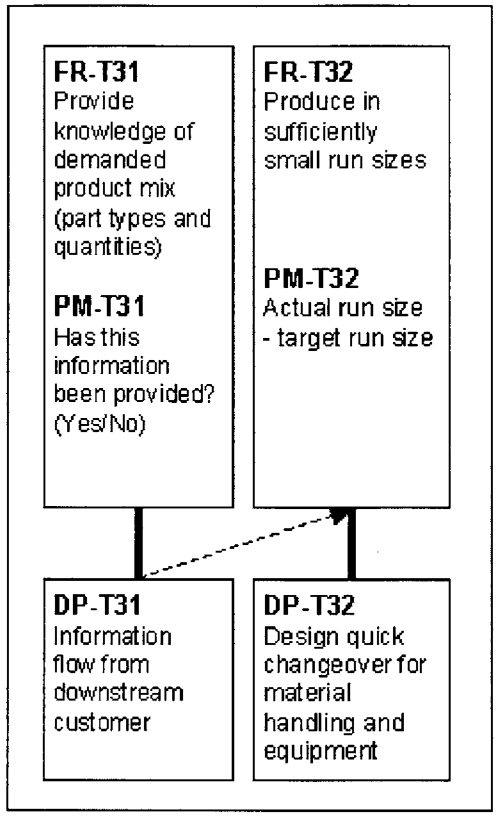


Figure 4.28: Middle Level of the Delay Reduction Branch of the MSD Decomposition

FR-T31: Provide knowledge of demanded product mix (part types and quantities)
PM-T31: Has this information been provided? (Y/N)

FR-T32: Produce in sufficiently small run sizes
PM-T32: Actual run size – target run size

The PMs shown in Figure 4.28 which develop from PM-T3 (run size delay) ensure that production can be leveled to meet customer demand. PM-T31 requires knowledge of the demanded product mix in terms of part types and part quantities so that the total production schedule may be leveled. PM-T32 measures the difference between the actual run size and the target run size so that actions may be taken to enable the manufacturing system to operate at the target run size.

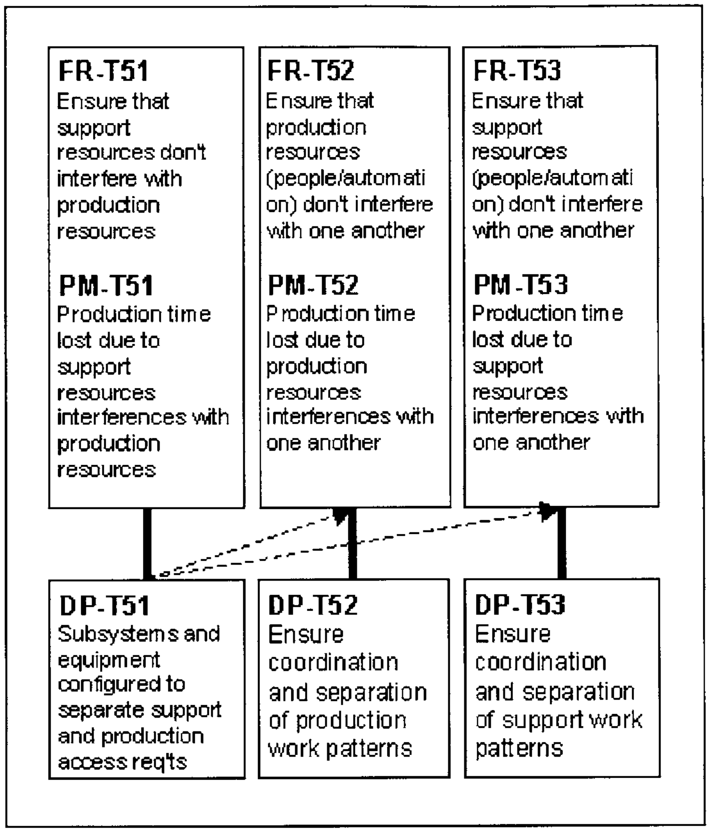


Figure 4.29: Middle Level of the Delay Reduction Branch of the MSD Decomposition

FR-T51: Ensure that support resources don't interfere with production resources

PM-T51: Production time lost due to support resources interferences 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 interferences 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 interferences with one another

The PMs shown in Figure 4.29 which arise from PM-T5 (systematic operational delays) ensure that production will not be interrupted due to interferences between and among the production and support resources. PM-T51 measures the time lost due to support resources interfering with production resources, i.e. material replenishment disrupting an operator adding value to a part. PM-T52 measures the time lost due to production resources interfering with one another, i.e. two operators getting in each other's way due to crossing workpaths. PM-T53 measures the time lost due to support resources interfering with one another, i.e. two material handlers getting in each other's way due to crossing workpaths.

4.3.5 Direct Labor Branch Performance Measurements

The Direct Labor branch of the MSD Decomposition spans levels 4 and 5. PMs have been defined for each of the FRs in this branch, as shown in Figure 4.30.

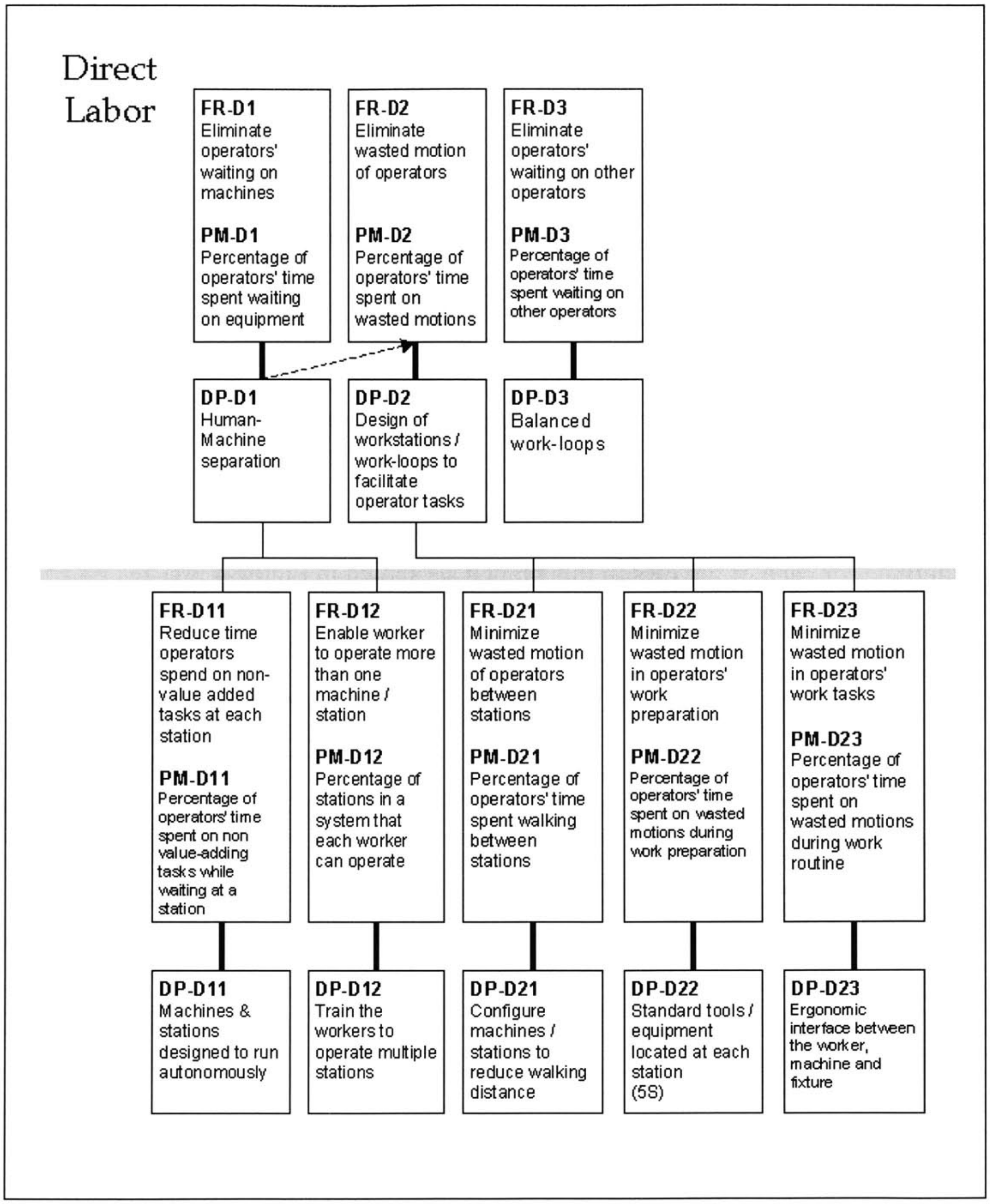


Figure 4.30: Direct Labor Branch of the MSD Decomposition

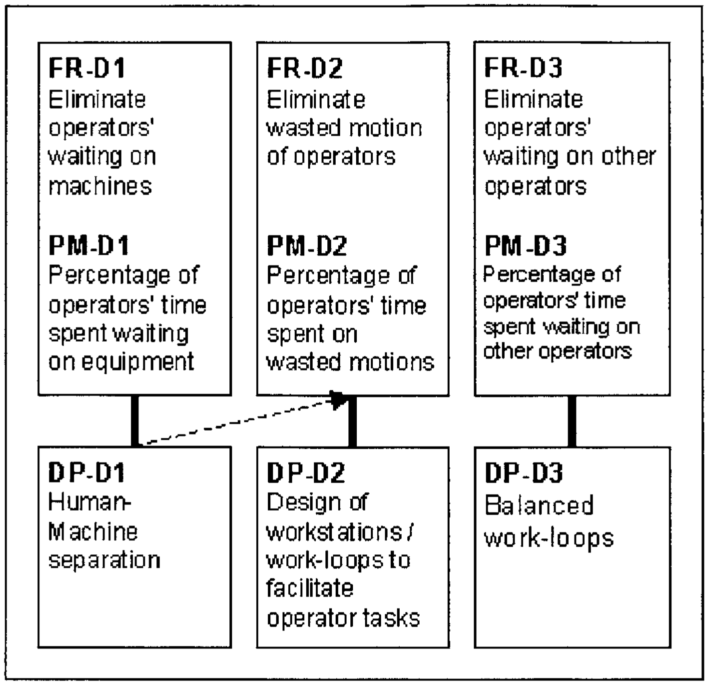


Figure 4.31: Top Level of the Direct Labor Branch of the MSD Decomposition

FR-D1: Eliminate operators' waiting on machines

PM-D1: Percentage of operators' time spent waiting on equipment

FR-D2: Eliminate wasted motion of operators

PM-D2: Percentage of operators' time spent on wasted motions

FR-D3: Eliminate operators' waiting on other operators

PM-D3: Percentage of operators' time spent waiting on other operators

The PMs for the Direct Labor branch shown in Figure 4.31 measure, in general, the percentage of operators' time that is spent on various non-value-adding tasks. PM-D1 measures the percentage of operators' time that is spent waiting on equipment to complete processing. PM-D2 measures the percentage of operators' time that is spent on wasted motions due to excessive walking or unnecessary work content. PM-D3 measures the percentage of operators' time that is spent waiting on other operators due to unbalanced work content among the operators. The goal is to reduce and eliminate, if possible, all these non-value-adding tasks which consume much of the operators' time.

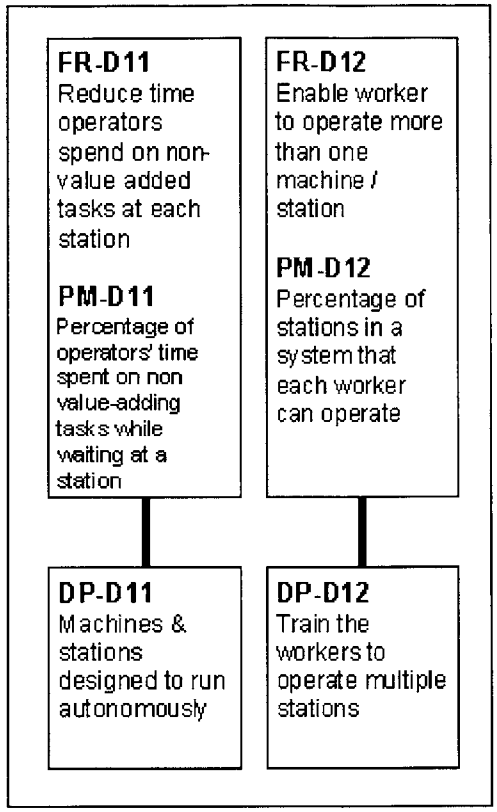


Figure 4.32: Lower Level of the Direct Labor Branch of the MSD Decomposition

FR-D11: Reduce time operators spend on non-value-added tasks at each station
PM-D11: Percentage of operators' 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

PMs-D11 and D12 shown in Figure 4.32 measure more specific aspects of the operators' time spent waiting on equipment. PM-D11 measures the percentage of operators' time that is spent on non-value-adding tasks while at a station so that operators spend most of their time on value-adding tasks. PM-D12 measures the percentage of stations that operators can operate in a manufacturing system so that the operators are able to work in all parts of the entire system.

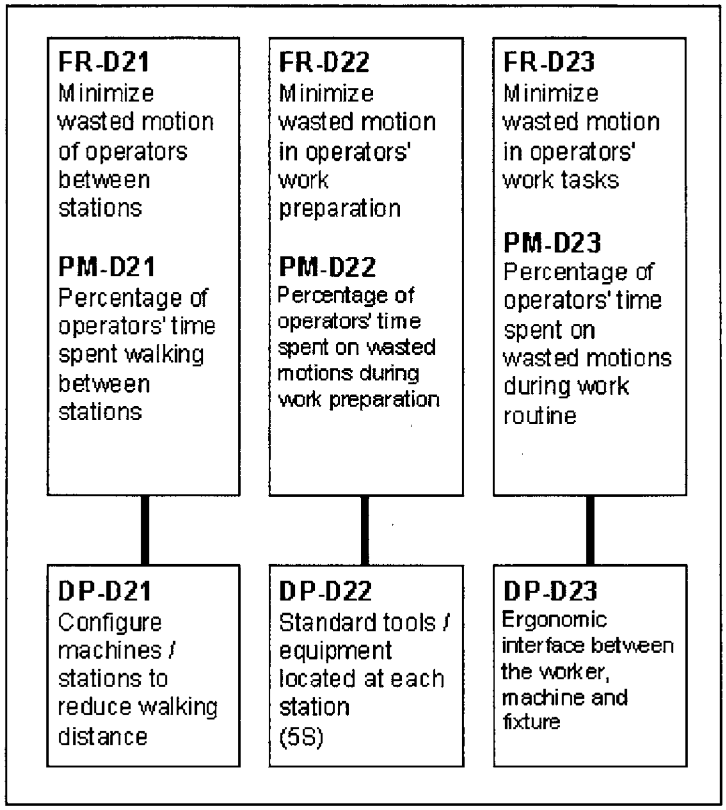


Figure 4.33: Lower Level of the Direct Labor Branch of the MSD Decomposition

FR-D21: Minimize wasted motion of operators between stations

PM-D21: Percentage of operators' time spent walking between stations

FR-D22: Minimize waste 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

PMs-D21, D22, and D23 shown in Figure 4.33 measure more specific aspects of the operators' time spent on wasted motions. PM-D21 measures the percentage of operators' time that is spent walking between stations so that stations will be laid out according to material flow. PM-D22 measures the percentage of operators' time that is spent on wasted motions for work preparation, such as searching for materials or tools, so that all necessary materials will be available to the operators when they are required. PM-D23 measures the percentage of operators' time that is spent on wasted motions during the work routine so that work stations and equipment will be designed ergonomically for operators.

4.3.6 Indirect Labor Branch Performance Measurements

The Indirect Labor branch of the MSD Decomposition covers only level 4. PMs have been defined for each of the FRs in this branch, as shown in Figure 4.34.

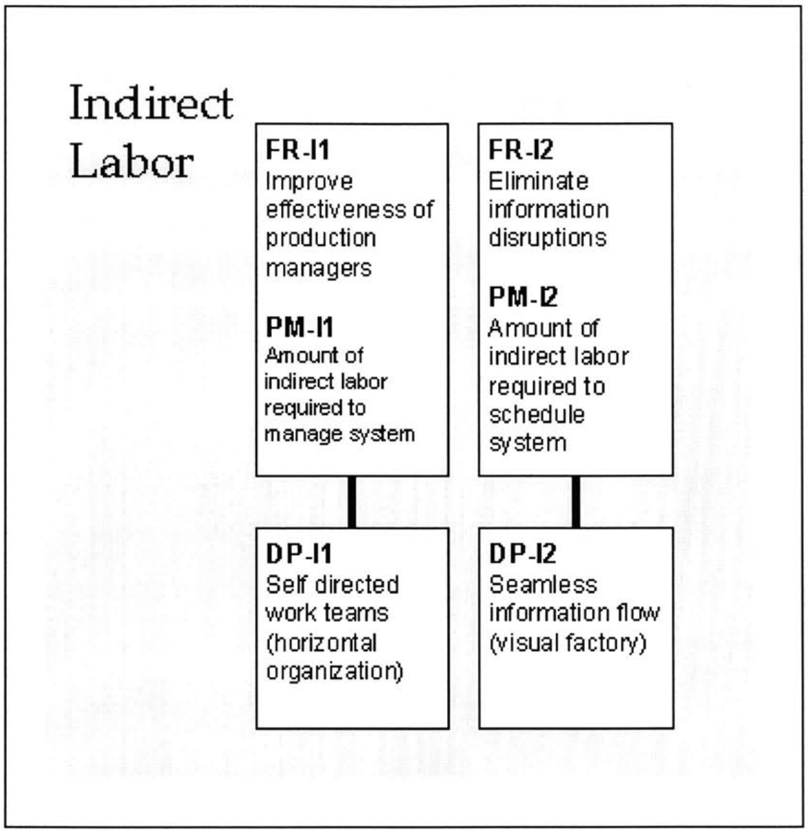


Figure 4.34: Indirect Labor Branch of the MSD Decomposition

FR-I1: Improve effectiveness of production 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

The PMs for the Indirect Labor branch measure the amount of indirect labor required in the manufacturing system. PM-I1 measures the amount of indirect labor required to manage the manufacturing system. This PM deals with the actual management structure which oversees the manufacturing system. PM-I2 measures the amount of indirect labor required to schedule the manufacturing system. This PM deals with the information flow from management which controls the behavior of the manufacturing system. The goal is to foster more efficient management and operation of the manufacturing system. Greater efficiency means operators and supervisors in the manufacturing system have increased responsibility for the success or failure of the manufacturing system, and the system should be very responsive to changes, which means the time lag between management decision-making and implementation of those decisions should be as short as possible.

4.4 Key Performance Measurements of the MSDD

4.4.1 Key High Level PMs

The key high level performance measures for the MSD Decomposition include the level 1 PM, return on investment; all the level 2 PMs, sales revenue, manufacturing costs, and investment; and all the level 3 PMs, process capability, percentage of on-time deliveries, the difference between mean throughput time and customer expected lead time, the percentage of operators' time spent on wasted motions and waiting, the amount of required indirect labor, and facilities cost.

Return on investment (PM1) is illustrated by Equation 4.1 of this chapter. The three components which are used to calculate ROI are sales revenue, manufacturing costs, and investment (PMs11, 12, and 13). These performance measures are already tracked in most manufacturing environments so they will be fairly straightforward to measure. However, these financial metrics give a very high level assessment in terms of a manufacturing system's overall cost performance, and they do not provide much feedback in terms of a manufacturing system's daily performance and efficiency. Therefore, these high level financial metrics have limited usefulness in designing a manufacturing system. The MSD Decomposition solves this problem by developing performance measurements which provide more information about a manufacturing system's daily performance and efficiency. These more useful, or key, performance measurements are identified in the following sections.

4.4.2 Key Level 3 PMs

4.4.2.1 Key Level 3 Quality and Time PMs

Process capability, percentage of on-time deliveries, and the difference between mean throughput time and customer expected lead time are three very important PMs to design a manufacturing system. Measuring process capability (PM111) will ensure that the quality of all processes in the manufacturing system will be continually improved. Process capability is typically measured in most manufacturing environments. Therefore, this measure may be easily calculated and used to gauge performance.

Measuring the percentage of on-time deliveries (PM112) will ensure that the manufacturing system strives to deliver all products and services when promised, neither later nor earlier. This metric may or may not already be measured in a manufacturing system, but it should be straightforward to attain this data. If a manufacturing system produces according to a schedule which is based on actual customer demand, all operators and managers should know immediately if the schedule is not met. With this rapid feedback about the production status, the manufacturing system can be much more responsive to problems, and any problems can be eliminated much more quickly so that they do not reoccur.

Measuring the difference between mean throughput time and customer expected lead time (PM113) will ensure that the manufacturing system is able to supply products and services in order to meet customer demand. Similar to the performance metric for the percentage of on-time deliveries, this metric should be visible if the manufacturing system produces according to a schedule. In order to obtain more detailed information on the actual mean throughput time of a manufacturing system, a value stream analysis may be conducted by following parts through production from beginning to end [Rother, Shook, 1998]. This performance metric is very key because meeting customer demand is of the greatest importance.

4.4.2.2 Key Level 3 Direct Labor and Indirect Labor PMs

The percentage of operators' time spent on wasted motions and waiting, the amount of required indirect labor, and facilities cost are three key performance measures related to the effectiveness of both direct and indirect labor and the effective use of facilities in the manufacturing system. It is important to prevent wasting the operators' time with non-value-adding tasks such as searching for tools or parts. Also, it is important to have just enough indirect labor to manage and schedule the manufacturing system to operate efficiently. Finally, facilities cost should be minimized so that the manufacturing system meets customer demand while using the minimum amount of facilities.

Measuring the percentage of operators' time spent on wasted motions and waiting (PM121) will provide information on the time utilization of the operators. Most, if not all, of the operators' time should be spent adding value to products or performing other necessary functions. All other activities, such as watching machines run, walking between work stations, searching for tools or parts, or waiting for other operators, are non-value-adding and should be eliminated as much as possible. This performance metric may be slightly difficult and time-consuming to measure in a manufacturing system. However, developing and implementing standard work combination charts for the operators and continuously improving the standard work definitions to eliminate all non-value-adding tasks will help improve this performance metric. Understanding the efficiency of the operators is very key so that the work stations and work content may be designed to eliminate waste.

Measuring the amount of required indirect labor in a manufacturing system (PM122) will provide information on the effectiveness of the managers and supervisors. This metric is intended to encourage more communication between managers, supervisors, and operators so that a manufacturing system is very responsive to changes, such as scheduling changes. A vertical, hierarchical management organization will be slow to implement changes so a move to more horizontal organization is advocated. Furthermore, this metric is intended to empower direct labor and give the operators more responsibility so that they feel a sense of ownership and pride for their work. This performance metric is very key in order to create a responsive manufacturing system led by an efficient management team.

Measuring the facilities cost in a manufacturing system (PM123) will provide information about the remainder of the costs of operation excluding direct and indirect labor. This metric is intended to help streamline the entire manufacturing system so that only the minimum amount of required facilities are used. Manufacturing systems which are designed according to material flow with balanced operations will usually require less facilities than manufacturing systems set up in large functional departments, which have complicated material flow and large amounts of inventory. This metric should be fairly straightforward to track in a manufacturing system, and it may already be measured regularly in most systems.

4.4.3 Key Quality PMs

The key performance measures for the Quality branch of the MSDD include PMs-Q11, Q12, Q13, and Q14. These PMs measure the number of defects per n parts assignable to equipment, operators, processes, and materials, respectively. The manufacturing system must be designed such that it provides immediate feedback to the operators and managers about quality problems. Measuring these four PMs provides information which is critical to eliminating the root causes for defects in a manufacturing system. It is very important to understand the sources of defects as soon as they occur so that the root causes may be eliminated. These performance metrics may be somewhat difficult to measure as they may require much time and effort. However, the level of quality which can be achieved by understanding and eliminating the root causes for defects more than justifies the time and effort which may be required to track these performance measures.

4.4.4 Key Identifying and Resolving Problems PMs

The key performance measure for the Identifying and Resolving Problems branch of the MSDD is PM-R1. This PM measures the time between the occurrence and resolution of disruptions in a manufacturing system. Measuring this time should lead to efforts to reduce the total time necessary to identify resolve problems. PM-R1, the highest level metric of this branch, is chosen as a key PM because it is fairly simple to measure relative to the lower level PMs of this branch, which are more specific segments of time involved in resolving problems. The lower level PMs may be useful in pinpointing which segment of the total time is the most problematic, but measuring each of these lower level PMs on a regular basis is far too time-consuming.

4.4.5 Key Predictable Output PMs

The key performance measures for the Predictable Output branch of the MSDD include PMs-P11, P12, P13, and P14. These PMs measure the number of occurrences of production disruptions due to information disruptions, equipment downtime, operator disruptions, and material shortages, respectively, and also measure the amount of production time lost due to each. The manufacturing system must be designed such that it provides immediate feedback to the operators and managers about production disruptions, similar to quality issues. Measuring these four PMs can provide information which is instrumental to reducing the number of disruptions in a manufacturing system. These performance measures should be easy to track if the causes of and time lost due to production disruptions are known immediately when they occur. Again, the lower level PMs of this branch may be useful in determining more specific information about each cause of production disruptions, but measuring each of these lower level PMs on a regular basis is both unnecessary and time-consuming.

4.4.6 Key Delay Reduction PMs

The key performance measures for the Delay Reduction branch of the MSDD include PMs-T1, T2, T3, T4 and T5. The first four PMs measure the levels of inventory due to lot delay, process delay, run size delay, and transportation delay, respectively. The last PM (PM-T5) measures the production time lost due to interferences between and among production and support resources. Measuring these PMs will provide information essential to eliminating all types of delays in the manufacturing system. It may be difficult to identify how much inventory is the result of each type of delay, but it is very key to understand all five delays and the methods to eliminate them, which have been discussed previously. The lower level PMs of this branch give more specific information which is useful in eliminating each type of delay and should be used whenever necessary.

4.4.7 Key Direct Labor PMs

The key performance measure for the Direct Labor branch of the MSDD is PM121, measuring the percentage of operators' time spent on wasted motions and waiting, as discussed in the Key Level 3 PMs section. The remainder of the PMs in this branch separate PM121 into more specific types of operator wastes: operators' waiting on machines, wasted motions of operators, and operators' waiting on other operators. These PMs are somewhat difficult to measure but can be very useful to eliminate non-value-adding tasks and unnecessary motions of the operators. A very effective way to eliminate the wastes in direct labor is to define and follow standard work combination charts. In addition, by continually improving the defined work standards and implementing the changes, all types of wastes in direct labor can be constantly eliminated.

4.4.8 Key Indirect Labor PMs

The key performance measure for the Indirect Labor branch of the MSDD is PM122, measuring the amount of required indirect labor, as discussed in the Key Level 3 PMs section. The remaining PMs in this branch separate PM122 into more specific types of indirect labor tasks. These PMs may be difficult to measure, but it is important to understand the amount of indirect labor which is really necessary to manage and schedule a manufacturing system. Too much indirect labor may hinder effective operation of the system because management decisions and changes may take a long time to be implemented. Also, different managers may try to implement contradicting changes due to a lack of communication between all of the managers and supervisors. Furthermore, too little indirect labor may also hinder effective operation of the system because a few managers and supervisors may not be able to manage and schedule an entire manufacturing system.

Chapter 5: Manufacturing System Design Evaluation Tool

5.1 Introduction to the Manufacturing System Design Evaluation Tool

When a system is as complex as a manufacturing plant, it is often very difficult to assess its design and operational performance. Manufacturing systems are traditionally measured with performance metrics such as unit labor cost and machine utilization, as well as a myriad of other financial measures. Most companies measure performance with management cost accounting systems [Kaplan and Cooper, 1998]. These measures are supposed to be indicators of performance and cost. This financial information has been said to give an outdated picture of operational health [Upton and Macadam, 1997]. More importantly, it does not lead to or point out system design weaknesses and opportunities for improvement.

It is far more important to design a manufacturing system well and measure the effectiveness of the system design. The Manufacturing System Design (MSD) Evaluation Tool described in this chapter shown in Figure 5.1 has been developed to assess the design of manufacturing systems, not their performance. This analysis tool is based on the Axiomatic Design [Suh, 1990] methodology and builds upon the 'lean' Manufacturing System Design Decomposition (MSDD) [Suh, Cochran and Lima, 1998]. The MSDD decomposes a generalized manufacturing system which is designed with the philosophy of the Toyota Production System (TPS) in mind [Monden, 1998]. Using the MSD Evaluation Tool, improvements may be directed in the most critical areas, and changes in design and capability can be documented.

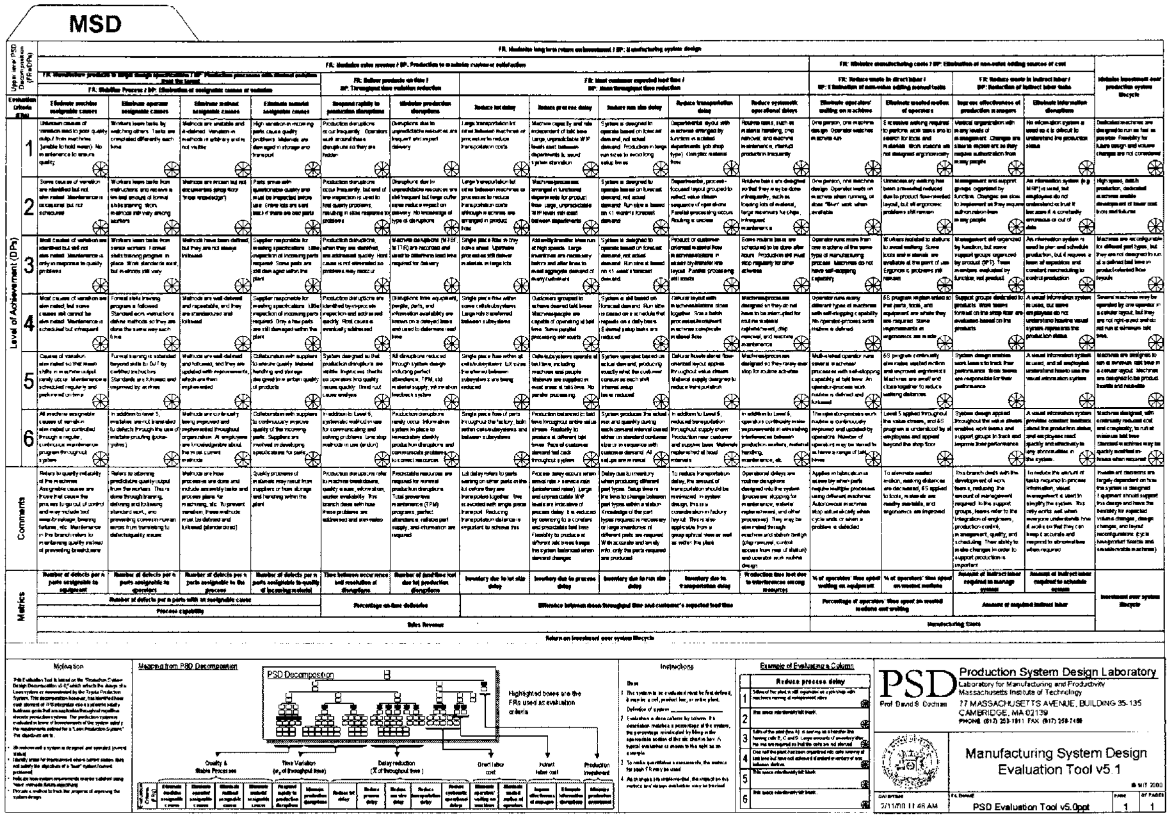


Figure 5.1: Manufacturing System Design (MSD) Evaluation Tool

The MSD Evaluation Tool measures how well a system is designed based on the criteria outlined in the MSD Decomposition. Six levels of manufacturing system design achievement have been defined: Job Shop or Departmental Layout, Departments Arranged by Product Flow, Assembly Line or Transfer Line, Pseudo-Cell, Assembly or Machining Cells, and Linked-Cell Manufacturing System. The Linked-Cell Manufacturing System is considered the highest physical achievement of system design known today. However, there are always continuous improvements which can be made to any design.

The MSD Evaluation Tool provides a method to evaluate qualitatively a manufacturing system design. By doing this, areas of the system design which need the most improvement can be identified easily. In addition, quantitive measures have been developed to aid in the assessment and improvement process. Finally, the MSD Evaluation Tool is aimed to be widely applicable to most repetitive, discrete-part manufacturing systems. The use of the MSD Evaluation Tool will be to assess and aid in the design of current and future manufacturing systems.

5.2 Motivation

5.2.1 Defining a 'Good' Design

An extremely important distinction that must be made is that the MSD Evaluation Tool attempts to evaluate the design of a manufacturing system instead of measuring its performance. This can be a difficult distinction to make because often, systems are evaluated based on cost performance alone. In addition, traditional performance measures such as commercial value, cost, quality, innovation and customer satisfaction are also measures of success. In manufacturing, many factors may contribute to the success or failure of the venture including many issues outside the realm of manufacturing such as product design, marketing and distribution. Therefore, assessing a manufacturing system based on traditional performance measures does not necessarily indicate the level of successful design, the level of successful implementation, or the opportunities for improvement in the manufacturing system. In order to address these issues, the goal is to evaluate the design, not the performance, of a manufacturing system.

In Axiomatic Design, an optimal design is characterized by independently satisfying the functional requirements with design parameters having the minimum information content [Suh, 1990]. In concept screening, the Pugh concept selection methodology is used [Pugh, 1991, Ulrich, Eppinger, 1995]. First, a selection matrix is formed with the potential concepts and weighted selection criteria. Second, each concept receives a score for each criterion multiplied by their weights, and the scores for all the criteria are summed for each concept. The concepts are then rank-ordered based on their scores. This method is used to aid in the selection or screening of concepts.

In the two approaches mentioned above, the design parameters or concepts are assessed by how each impacts the many functional requirements or design selection criteria. This type of approach will be followed in this chapter, again in the context of Axiomatic Design.

5.2.2 Impact of Evaluation Methods on System Evolution

An important theme of the Production System Design laboratory is that designing a manufacturing system to satisfy operation-based performance metrics leads to poorly designed systems. The performance measurements must be aligned with the functional requirements of the manufacturing system design. In this way, the performance metrics will support and promote the functional requirements of the system as shown in the previous Performance Measurements chapter. The MSD Evaluation Tool discussed in this chapter defines a gradient of DPs to satisfy the FRs of a manufacturing system design. All of the DPs together represent a tool for system design, but merely implementing some of the DPs does not mean that a coherent system design is in place. The tool is only a design guideline to evaluate sections of a manufacturing system design.

The classic example of operation-based performance metrics is the focus on machine utilization and direct labor costs. In order to ensure that machines are fully utilized, workers monitor them (one machine, one operator) to keep the uptime maximized. In addition, in order to decrease direct labor costs, the number of machines is reduced, resulting in extremely fast, complex machines grouped in functional departments. Throughput time, inventory, and quality traceability are all sacrificed in this system. The Toyota Production System addresses these problems by arranging machines in cells according to product flow. The cells are designed so that an operator can run several machines, as long as the manual cycle time is less than or equal to the system takt time. In this system, machine utilization may be lower, but the machine designs are simplified to achieve a desired system takt time. Quality issues are resolved quickly, inventory levels and throughput times are low, workers are more efficient, the system has greater flexibility, and continuous improvement is enabled.

The above description is a very abbreviated comparison between departmental and cellular manufacturing [Cochran and Dobbs, 1999]. It illustrates that management cost accounting drives the manufacturing system design, and it should not [Cochran, Kim, and Kim, 2000].

5.2.3 Current 'Lean' Production Assessments

As the implementation of 'lean' manufacturing becomes more widespread, companies and consultants have developed methods to evaluate how 'lean' their manufacturing systems are. These evaluation tools observed at Toyota, Ford, Visteon and Boeing, just to name a few, are very similar in nature. These tools rate systems based on certain criteria, which may include management involvement, levels of inventory, scheduling methods, implementation of cells, standardization, man-machine separation and shop floor attitudes. In each of these categories, levels are defined which qualitatively describe achievements from poorly operated 'mass' production to the ultimate in 'lean' production as depicted in Figure 5.2.

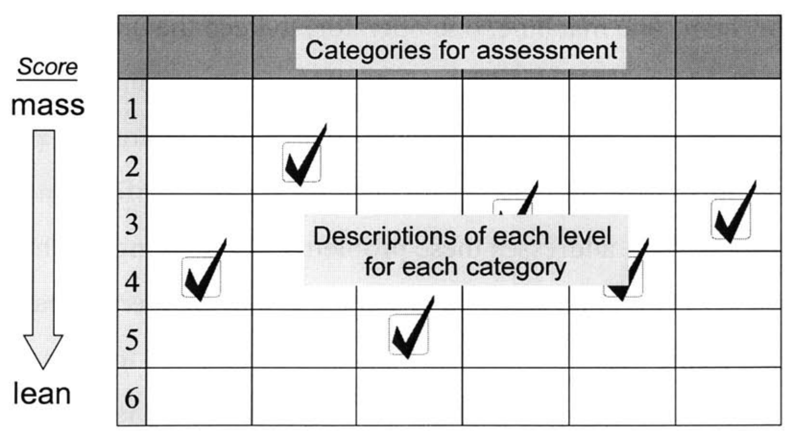


Figure 5.2: Typical 'Lean' Evaluation Chart

These evaluation tools are designed to allow someone to visit a manufacturing plant and through physical observation, to make an assessment on how 'lean' the system is and where improvements should be made. This evaluation can be done because many of the elements of TPS are visible, such as U-shaped cells, standardization, low levels of inventory and workpace.

Although these assessments indicate whether a manufacturer looks like Toyota and may give some direction for improvements, they do not reflect how the tools are being used to achieve the objectives of the manufacturing system design. This chapter presents a structured method to analyze a manufacturing system to identify whether the objectives of the system design adhere to the objectives of 'lean'. In addition, the impact of elements on each other and on upper level requirements is shown. This approach provides the user with a better understanding of the system and a better idea of where to concentrate improvement efforts.

5.3 Development of the MSD Evaluation Tool

5.3.1 Foundation of the MSD Evaluation Tool - the MSD Decomposition

The MSD Decomposition shown in Figure 5.3 is a generalized model of a manufacturing system design, which has been developed using Axiomatic Design. The FRs may be assessed to determine how well the design adheres to this decomposition. It should be noted that the MSD Decomposition is a decoupled, path-dependent design.

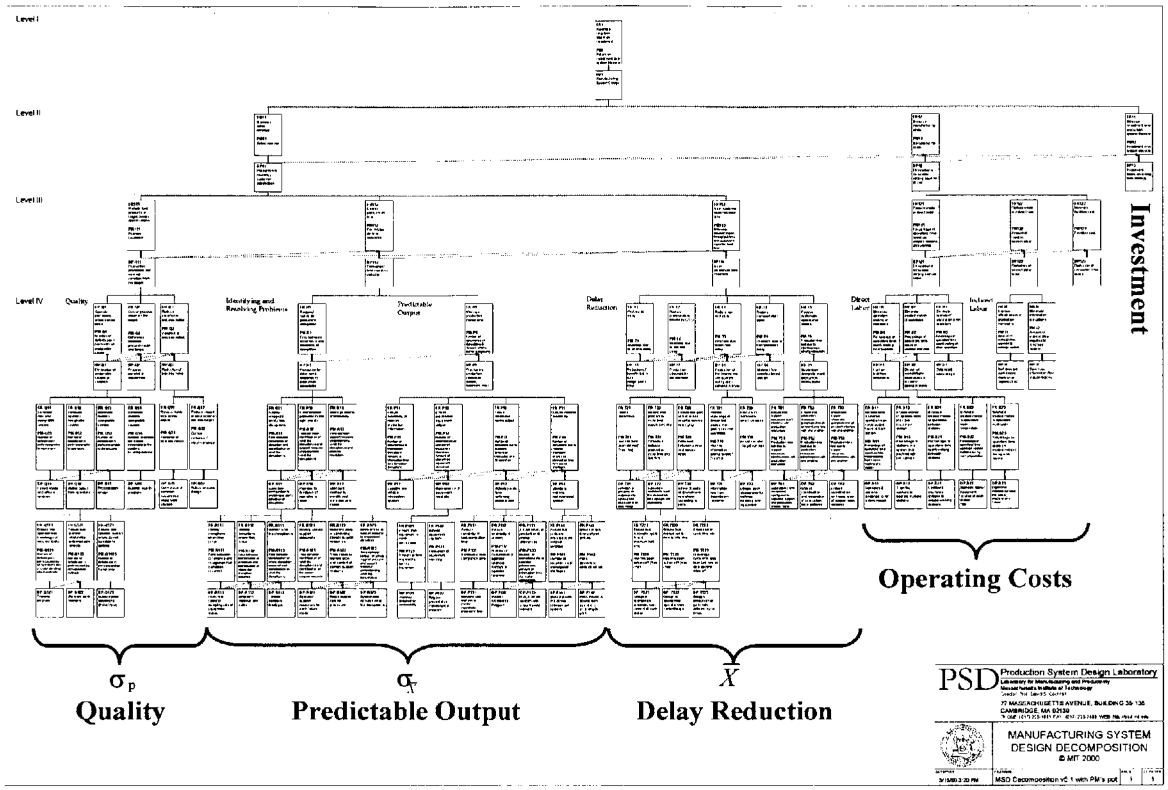


Figure 5.3: Manufacturing System Design (MSD) Decomposition

The MSD Decomposition has five branches of functional requirements: Quality, Predictable Output, Delay Reduction, Operating Costs, and Investment.

The Quality (σ_p) branch decomposes the FRs of achieving quality output from the processes of the system. The Predictable Output (σ_X) branch decomposes FRs of reducing variation in the manufacturing throughput time. The Delay Reduction ($\bar{X}$) branch decomposes the FRs of reducing the mean manufacturing throughput time. The Operating Costs branch decomposes the FRs of minimizing the costs of direct and indirect labor. The Investment branch decomposes the FRs of minimizing the total investment for a system.

5.3.2 *Determining Which Level of the Decomposition to Evaluate: Design Phase and Implementation Phase*

The MSD Decomposition has been developed by determining the functional requirements (FRs) for a manufacturing system design and the corresponding design parameters (DPs). Each FR can be satisfied by many different DPs. From these possible choices, one DP, which matches the overall manufacturing system objectives, is chosen to satisfy each FR (Design Phase). This Design Phase is shown in the left side of Figure 5.4.

Each FR can then be evaluated based on how effectively its chosen DP has been implemented after design (Implementation Phase). This Implementation Phase is shown in the right side of Figure 5.4. The MSD Evaluation Tool evaluates the effectiveness of a chosen DP satisfying its FR.

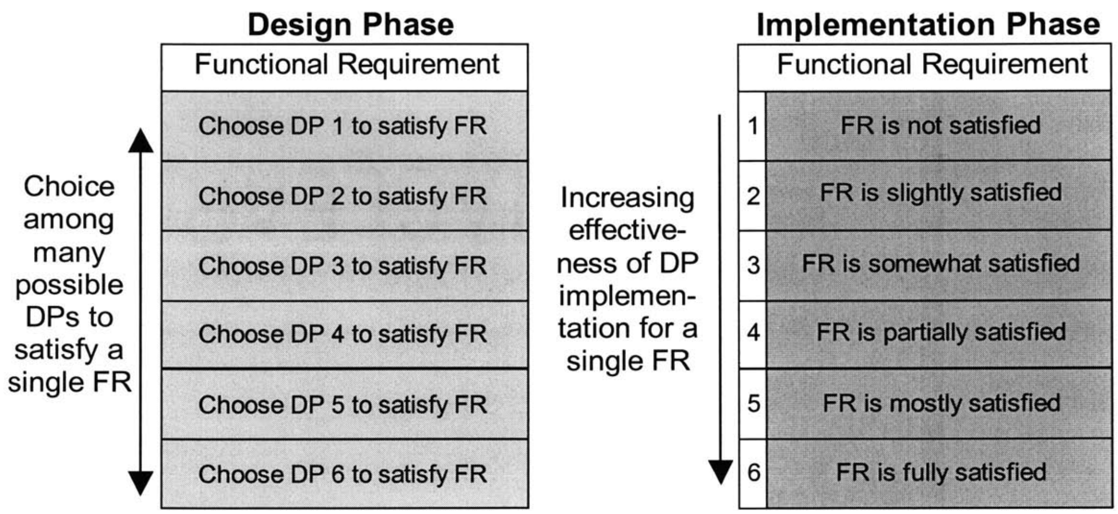


Figure 5.4: Design Phase – Choosing a DP to satisfy an FR
Implementation Phase – Evaluating implementation of a DP

5.3.2.1 *Design Phase - Choosing Among Different DPs for each FR*

In the Design Phase, the different possible DPs for a single FR must be identified and compared. This comparison can be done by following the two design axioms of

Axiomatic Design. DPs which maintain the independence of the FRs and which contain the minimum information are most desirable. In addition, the chosen DP should be aligned with the overall manufacturing system objectives.

An example from the MSD Decomposition related to quality in a manufacturing system is shown in Figure 5.5. A DP must be chosen to satisfy FR 111 'Manufacture products to target design specifications.' There are several possible DPs which can ensure that defects are not delivered. One possible DP is to scrap an entire lot of parts if a defect is found in that lot. A second possible DP is to use 100% inspection and rework to fix defects. A third possible DP is to improve the processes enough such that only human errors can lead to defects. A fourth possible DP is to design the system with integrated quality such that defects cannot be made at all.

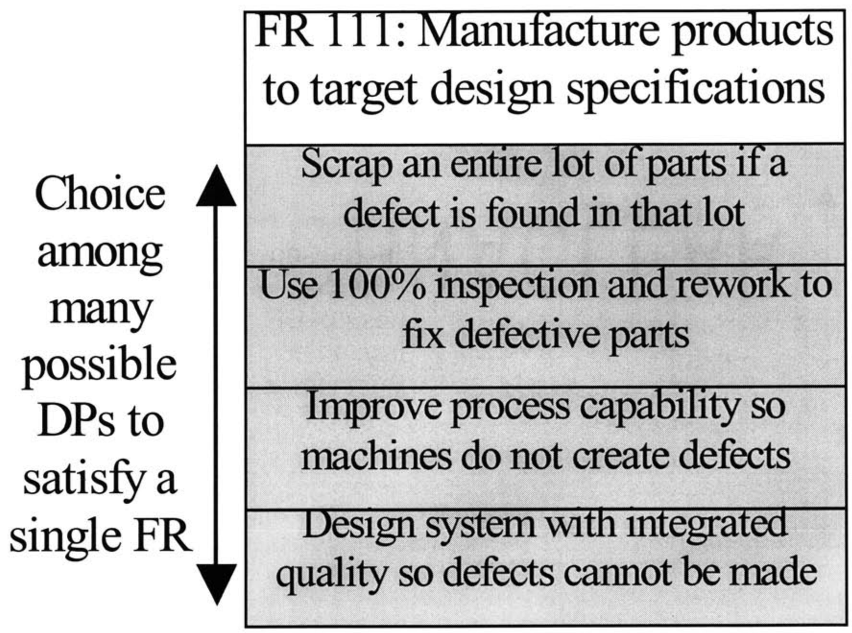


Figure 5.5: Design Phase Example – Choosing a DP for Quality

Although all four possible DPs can satisfy FR 111, they must be analyzed with respect to their impact on other FRs. In the MSD Decomposition, the production of defects immediately impacts delivering products on time and meeting customer expected lead time, shown by the Design Matrix in Figure 5.6. Because it is very important to avoid producing defects rather than detecting and reworking the parts, the fourth possible DP is chosen for FR 111. This DP, which states to design the system with integrated quality such that defects cannot be produced, is labeled DP 111 'Production processes with minimal variation from the target' in Figure 5.6.

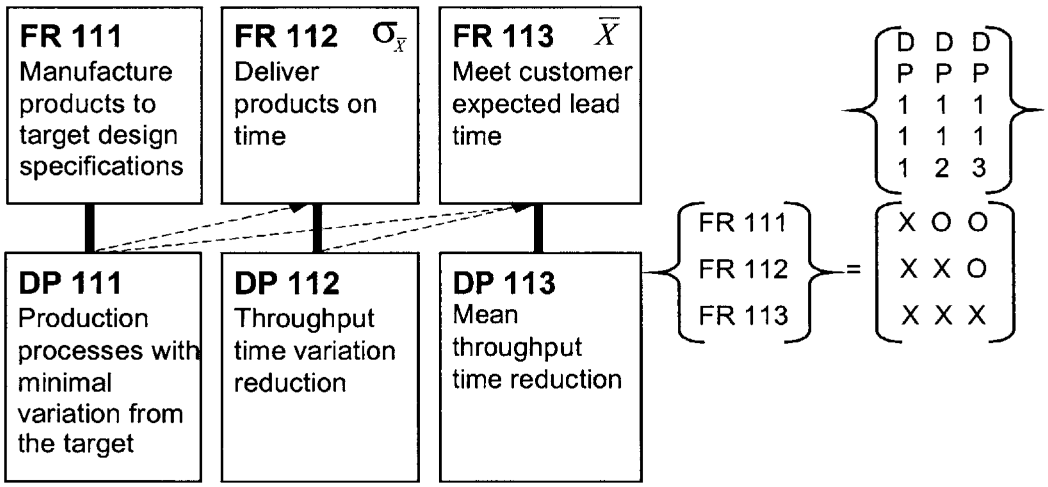


Figure 5.6: MSD Decomposition (Level 3: Maximizing Customer Satisfaction) with the Design Matrix

5.3.2.2 Implementation Phase – Evaluating the Effectiveness of a DP in Satisfying each FR

In the Implementation Phase, the satisfaction of each FR is evaluated based on how well the chosen DP is implemented in the system. For each FR, a DP has been chosen which coincides with the overall manufacturing system objectives. However, the chosen DP can be implemented with varying levels of success, and it is important to understand how successfully it has been implemented. An example from the MSD Decomposition of FR-D1 'Eliminate operators' waiting on machines' is presented in Figure 5.7.

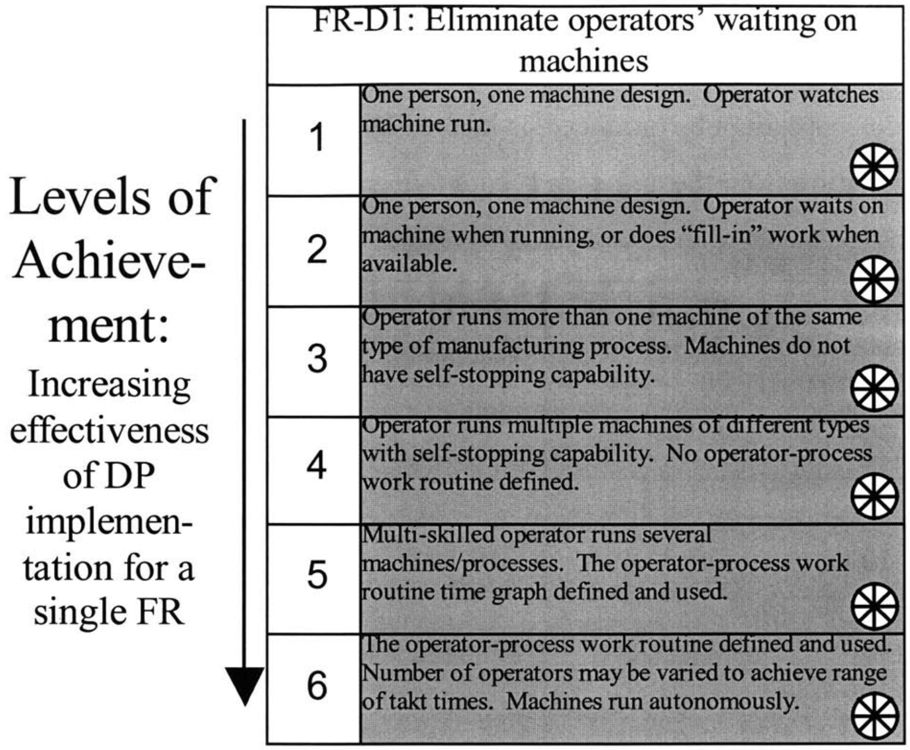


Figure 5.7: Implementation Phase Example – Evaluating the DP Implementation Effectiveness of FR-D1

In this example, FR-D1 'Eliminate operators' waiting on machines' is being evaluated based on how well DP-D1 'Human-Machine Separation' has been implemented. Six levels of achievement have been defined for this FR-DP pair. Level 1 is the worst, in which an operator watches the machine run; this obviously does not satisfy the FR. Level 6 is the best achievement, in which operators have defined work routines and machines run autonomously upon operator instruction; this achieves the FR unquestionably. Using this approach, it is possible to describe the implementation of a new or existing manufacturing system design with respect to achievement of the FRs of the system design.

5.3.3 *Development of the MSD Evaluation Tool Based on the MSD Decomposition*

The MSD Evaluation Tool is directly linked to the MSD Decomposition. In general, the Level 4 FRs of the MSD Decomposition are used as evaluation criteria in the MSD Evaluation Tool. Figure 5.8 shows exactly which FRs of the MSD Decomposition are used as evaluation criteria for the MSD Evaluation Tool. The singular importance of the MSD Evaluation Tool over traditional assessment methods is the fact that it evaluates the system design, not the system performance.

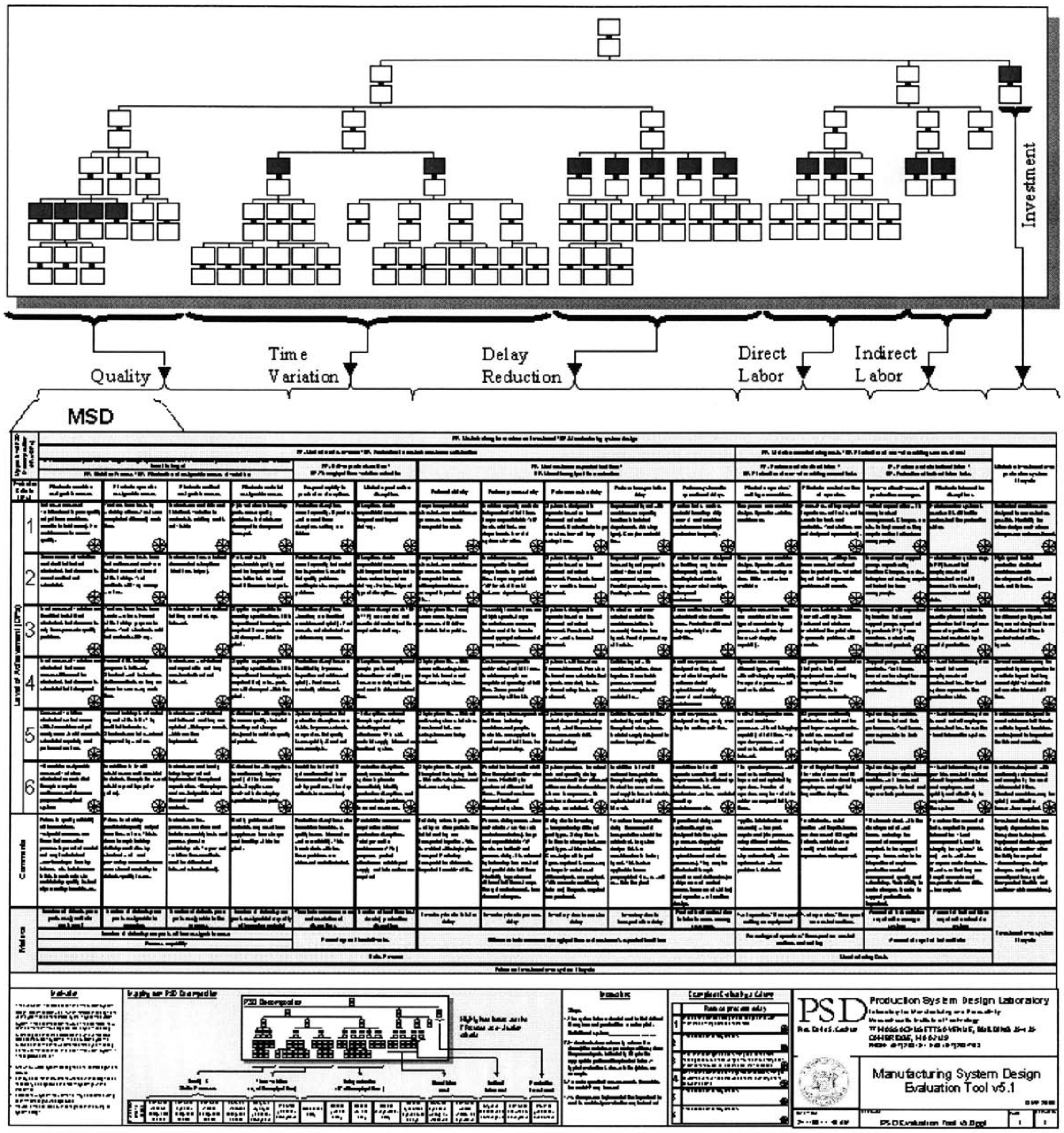


Figure 5.8: Derivation of the MSD Evaluation Tool from the MSD Decomposition

Using higher level FRs of the MSD Decomposition for the MSD Evaluation Tool may create a tool that is too general to provide an effective assessment whereas using lower level FRs may result in a tool that is too specific to offer a useful assessment tool across a wide range of manufacturing environments. The complete MSD Evaluation Tool is shown in Figure 5.9.

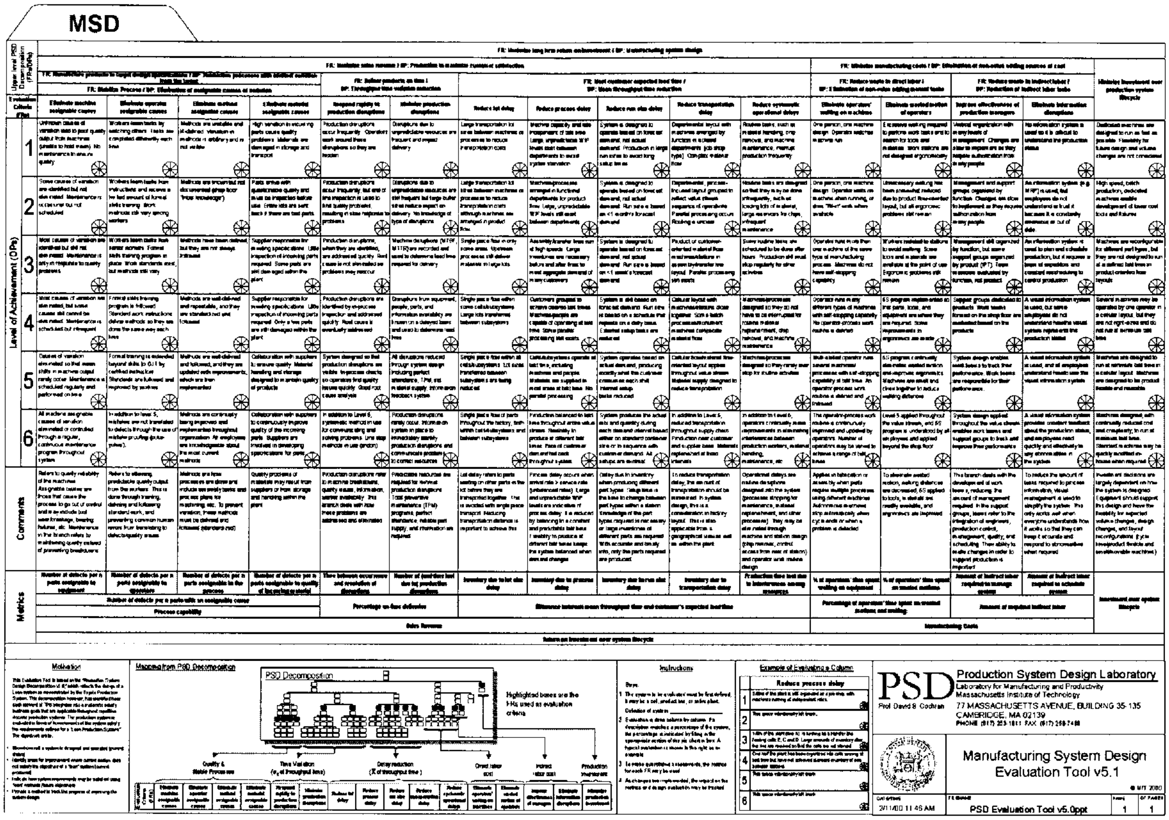


Figure 5.9: Manufacturing System Design (MSD) Evaluation Tool

5.3.4 Definition of Levels of Achievement

The evaluation criteria of the MSD Evaluation Tool have been selected from the FRs of the MSD Decomposition as shown in Figure 5.8; now, the evaluation approach is developed. For each evaluation FR, there are six levels of DP achievement:

Level 1: Job Shop or Departmental Layout

Level 2: Departments Arranged by Product Flow

Level 3: Assembly Line or Transfer Line

Level 4: Pseudo-Cell

Level 5: Assembly or Machining Cells Only

Level 6: Linked-Cell Manufacturing System

Level 1 is the most basic, traditional manufacturing system, which is not designed from a system perspective at all. Level 6 is the ultimate achievement of a manufacturing system design based on the MSD Decomposition. The six levels of achievement for each of the evaluation criteria of the MSD Evaluation Tool will be discussed in greater detail in a later section of this chapter.

5.3.4.1 Example: FR 111 'Manufacture products to target design specifications'

One of the main ways in which a manufacturing system increases customer satisfaction is delivering perfect quality. A survey of automobile manufacturers [Womack, Jones, Roos, 1991] showed that some non-Japanese manufacturers were able to achieve quality comparable to Japanese manufacturers based on the number of defects per 100 cars. However, the non-Japanese manufacturers achieved this quality with end-of-line rework areas using highly skilled technicians while the Japanese manufacturers achieved this quality without expensive, time-consuming rework.

The basis for integrated quality is dependent upon each process supplying only good parts to subsequent processes [Monden, 1998]. The key point here is that in order to produce to target design specifications, defects must not be produced (waste of producing defects). Integrating quality control [Black, 1991] also eliminates wastes of repairing, reworking, or replacing bad parts. Achieving this degree of quality also reduces variation in production, which allows less inventory between processes and enables consistent, on-time delivery.

In order to assess the manufacturing system design in terms of quality, the following levels of achievement have been defined for FR 111 'Manufacture products to target design specifications.'

Level 1

Defects are delivered to the customer. FR 111 is not fulfilled.

Level 2

End-of-line inspection is used to ensure no defects are delivered. FR 111 is beginning to be fulfilled by the use of rework areas, but there are high levels of scrap, as well as wasted manufacturing efforts.

Level 3

In-line, dedicated inspection stations used to catch defects earlier, as well as end-of-line inspection. FR 111 is somewhat fulfilled although scrap levels and wasted manufacturing efforts are reduced.

Level 4

Inspection is integrated into the line, but the root causes of defects are not identified or eliminated. Therefore, the same defects occur repeatedly. FR 111 is partially fulfilled.

Level 5

The transition to defect-free production has been made. Root cause analysis has been implemented, eliminating assignable sources of quality problems so that production is now predictable. Inspection is integrated into operator work patterns. The response time to eliminate problems has been greatly reduced. FR 111 is mostly fulfilled.

Level 6

Defects cannot be made because all processes are capable, reliable, and predictable. Root causes of defects resulting from equipment, operators, methods, and materials are identified and eliminated. All operations are standardized and mistake proofed (e.g. poka-yoke devices [Shingo, 1981]). In addition, both processes and operator work patterns are continually improved to prevent production of defects. FR 111 is completely fulfilled.

5.3.5 Qualitative Evaluation

After the six levels of achievement have been defined for each FR evaluated by the MSD Evaluation Tool, there must be some method of scoring a manufacturing system design. Therefore, a qualitative scoring method has been developed, shown in Figure 5.10.

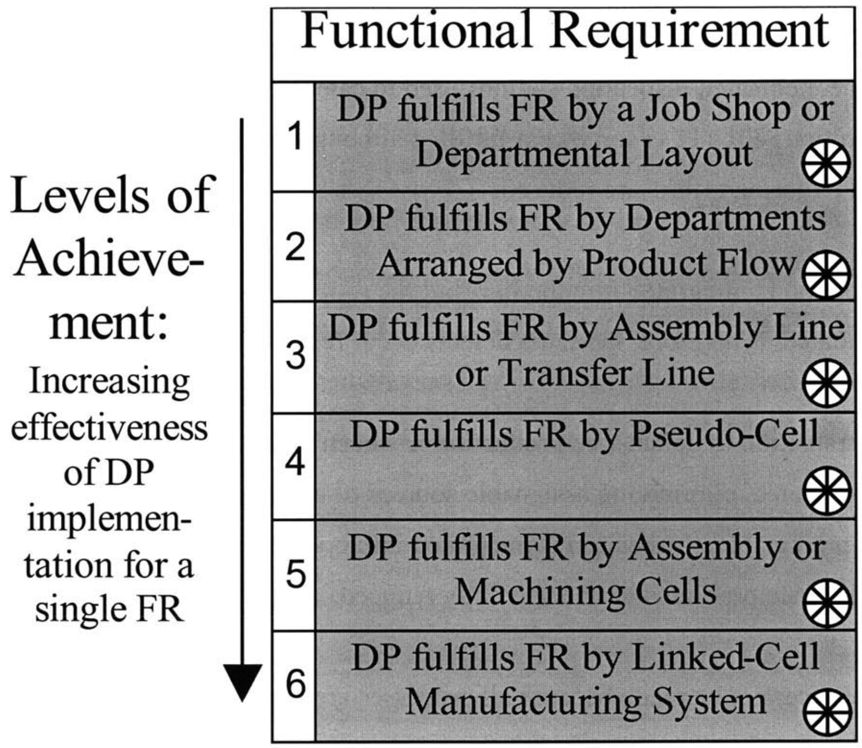


Figure 5.10: Qualitative Pie-Chart Scoring Method Example

In order to evaluate a system design, the actual characteristics of the plant are matched to the closest description among the six levels of achievement. Because it is unlikely that an entire plant has uniform characteristics, it may be necessary to score part of a plant at Level 3 and score another part of the plant at Level 5, for example.

As a result, the pie-chart scoring method was developed. The pies at each level of achievement represent the percentage of the plant that has achieved the indicated level. For each FR, or column, the total pie-chart score should add up to 100%. By using this scoring method, it becomes visually apparent which areas of the manufacturing system design need the most concentrated improvement efforts.

5.3.6 Quantitative Evaluation

Along with the qualitative evaluation just described, the FRs of the MSD Evaluation Tool may also be quantitatively evaluated. To this end, performance metrics have been aligned with each FR of the MSD Evaluation Tool. Each of the performance metrics is stated below its corresponding column in the MSD Evaluation Tool.

Also, more general performance metrics have been developed. For example, the highest level performance metric is return on investment (ROI), corresponding to FR 1 'Maximize long-term return on investment' of the MSD Decomposition. The derivation of performance measurements for all the FRs of the MSD Decomposition has been discussed in greater detail in the Performance Measurement chapter.

5.4 Discussion of the Levels of Achievement for each Evaluation Criterion of the MSD Evaluation Tool

5.4.1 FR-Q11 'Eliminate machine assignable causes'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-Q11 'Eliminate machine assignable causes' is shown in Figure 5.11.

FR-Q11: Eliminate machine assignable causes	
1	Unknown causes of variation lead to poor quality output from machines (unable to hold mean). No maintenance to ensure quality.
2	Some causes of variation are identified but not eliminated. Maintenance is occasional but not scheduled.
3	Most causes of variation are identified but still not eliminated. Maintenance is only in response to quality problems.
4	Most causes of variation are eliminated, but some causes still cannot be eliminated. Maintenance is scheduled but infrequent.
5	Causes of variation eliminated so that mean shifts in machine output rarely occur. Maintenance is scheduled regularly and performed on time.
6	All machine assignable causes of variation eliminated or controlled through a regular, continuous maintenance program throughout system.

Figure 5.11: FR-Q11 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design eliminates assignable causes of variation due to machines and equipment. The causes of variation attributable to machines and equipment first must be identifiable in the system. Once the causes are identified, they must be reduced and/or eliminated so that quality problems do not continually reoccur. Furthermore, machines must be maintained regularly in order to establish a consistent level of quality.

5.4.2 FR-Q12 'Eliminate operator assignable causes'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-Q12 'Eliminate operator assignable causes' is shown in Figure 5.12.

FR-Q12: Eliminate operator assignable causes	
1	Workers learn tasks by watching others. Tasks are completed differently each time.
2	Workers learn tasks from instructions and receive a limited amount of formal skills training. Work methods still vary among workers.
3	Workers learn tasks from senior workers. Formal skills training program in place. Work standards exist but methods still vary.
4	Formal skills training program is followed. Standard work instructions define methods so they are done the same way each time.
5	Formal training is extended beyond skills to OJT by certified instructors. Standards are followed and improved by workers.
6	In addition to Level 5, mistakes are not translated to defects through the use of mistake proofing (poka-yokes)

Figure 5.12: FR-Q12 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design eliminates assignable causes of variation due to operators. The operators first must have sufficient training in order to complete the required tasks. Once the operators have the necessary skills, they must follow standardized work instructions to ensure that the tasks are performed in the same manner consistently by all operators. Moreover, operators should suggest and implement improvements to the standardized work instructions. Finally, because operators may occasionally make mistakes, operations should be mistake-proofed as much as possible in order to prevent the accidental production of defects. This mistake-proofing can be done by methods such as poka-yoke devices [Shingo, 1981].

5.4.3 FR-Q13 'Eliminate method assignable causes'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-Q13 'Eliminate method assignable causes' is shown in Figure 5.13.

FR-Q13: Eliminate method assignable causes	
1	Methods are unstable and ill-defined. Variation in methods is arbitrary and is not visible.
2	Methods are known but not documented (shop floor "tribal knowledge").
3	Methods have been defined, but they are not always followed.
4	Methods are well-defined and repeatable, and they are standardized and followed.
5	Methods are well-defined and followed, and they are updated with improvements, which are then implemented.
6	Methods are continually being improved and implemented throughout the organization. All employees are knowledgeable about the most current methods.

Figure 5.13: FR-Q13 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design eliminates assignable causes of variation due to methods. Manufacturing methods must be well-defined and documented in a manufacturing system. More importantly, the operators must always follow the standardized work methods. Similar to FR-Q12, the standardized work methods should be improved continuously, and these changes in methods should be implemented by all operators.

5.4.4 FR-Q14 'Eliminate material assignable causes'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-Q14 'Eliminate material assignable causes' is shown in Figure 5.14.

FR-Q14: Eliminate material assignable causes	
1	High variation in incoming parts cause quality problems. Materials are damaged in storage and transport.
2	Parts arrive with questionable quality and must be inspected before use. Entire lots are sent back if there are bad parts.
3	Supplier responsible for meeting specifications. Little inspection of incoming parts required. Some parts are still damaged within the plant.
4	Supplier responsible for meeting specifications. Little inspection of incoming parts required. Only a few parts are still damaged within the plant.
5	Collaboration with suppliers to ensure quality. Material handling containers designed to maintain quality of products.
6	Collaboration with suppliers to continuously improve quality of the incoming parts. Suppliers are involved in developing specifications for parts.

Figure 5.14: FR-Q14 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design eliminates assignable causes of variation due to materials. High variation in incoming parts to a manufacturing system can cause many quality problems which may not be easily detected or rectified. Therefore, customers and suppliers must work together to meet material specifications so that incoming parts have reliable quality. In addition, material handling and storage should not compromise the quality of the products.

5.4.5 FR-R1 'Respond rapidly to production disruptions'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-R1 'Respond rapidly to production disruptions' is shown in Figure 5.15.

FR-R1: Respond rapidly to production disruptions	
1	Production disruptions occur frequently. Operators work around these disruptions so they are hidden.
2	Production disruptions occur frequently, but end of line inspection is used to find quality problems, resulting in slow response to problems.
3	Production disruptions, when they are identified, are addressed quickly. Root cause is not eliminated so problems may reoccur.
4	Production disruptions are identified by in-process inspection and addressed quickly. Root cause is eventually addressed.
5	System designed so that production disruptions are visible. In-process checks so operators find quality issues quickly. Good root cause analysis.
6	In addition to Level 5, systematic method in use for communicating and solving problems. Line stop methods in use (andon).

Figure 5.15: FR-R1 Column of the MSD Evaluation Tool

This column evaluates how rapidly a manufacturing system design responds to production disruptions. Operators must be aware of quality problems when they occur. When problems occur, they should be resolved as quickly as possible in order to continue production. The root cause of quality problems should be eliminated so that the same problems do not reoccur in a manufacturing system. A manufacturing system designed with a systematic method in use for communicating and resolving problems will be able to identify and eliminate quality problems rapidly and effectively.

5.4.6 *FR-P1 'Minimize production disruptions'*

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-P1 'Minimize production disruptions' is shown in Figure 5.16.

FR-P1: Minimize production disruptions	
1	Disruptions due to unpredictable resources are frequent and impact delivery.
2	Disruptions due to unpredictable resources are still frequent, but large buffer sizes reduce impact on delivery. No knowledge of type of disruptions.
3	Machine disruptions (MTBF, MTTR) are recorded and used to determine lead time required for delivery.
4	Disruptions from equipment, people, parts and information availability are known on a delayed basis and used to determine lead time.
5	All disruptions reduced through system design including perfect attendance, TPM, std. material supply, information feedback system.
6	Production disruptions rarely occur. Information system in place to immediately identify production disruptions and communicate problems to the correct support resources.

Figure 5.16: FR-P1 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design minimizes the frequency of production disruptions. Four causes of production disruptions have been identified: equipment, operators, materials, and information availability. Examples of methods to prevent disruptions due to these four causes include total preventive maintenance, perfect attendance, standard material supply, and information feedback systems. When a disruption occurs, it should be identified, and the root cause for the production disruption should be eliminated. In this way, the variation in throughput time for a manufacturing system can be very low and predictable.

5.4.7 FR-T1 'Reduce lot delay'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-T1 'Reduce lot delay' is shown in Figure 5.17.

FR-T1: Reduce lot delay	
1	Large transportation lot sizes between machines or processes to reduce transportation costs.
2	Large transportation lot sizes between machines or processes to reduce transportation costs although machines are arranged in product flow.
3	Single piece flow in only some areas. Upstream processes still deliver materials in large lots.
4	Single piece flow within some cells/subsystems. Large lots transferred between subsystems.
5	Single piece flow within all cells/subsystems. Lot sizes transferred between subsystems are being reduced.
6	Single piece flow of parts throughout the factory, both within cells/subsystems and between subsystems.

Figure 5.17: FR-T1 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design reduces lot delay. Parts should flow through a manufacturing system in single piece flow. The transition to single piece flow should be made first within cells, then between upstream and downstream cells, and ultimately between upstream and downstream subsystems. In some specific manufacturing systems, it may not be feasible to produce parts in single piece flow. However, it is advantageous to produce parts in the smallest lot sizes possible.

5.4.8 *FR-T2 'Reduce process delay'*

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-T2 'Reduce process delay' is shown in Figure 5.18.

FR-T2: Reduce process delay	
1	Machine capacity and rate independent of takt time. Large, unpredictable WIP levels exist between departments to avoid system starvation.
2	Machines/processes arranged in functional departments for product flow. Large, unpredictable WIP levels still exist between departments.
3	Assembly/transfer lines run at high speeds. Large inventories are necessary before and after lines to meet aggregate demand of many customers.
4	Customers grouped to achieve desired takt times. Machines/people are capable of operating at takt time. Some parallel processing still exists.
5	Cells/subsystems operate at takt time, including machines and people. Materials are supplied in most areas at takt time. No parallel processing.
6	Production balanced to takt time throughout entire value stream. Flexibility to produce at different takt times. Pace of customer demand fed back throughout manufacturing system.

Figure 5.18: FR-T2 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design reduces process delay. At Level 1, machines produce at a rate which is not aligned with customer demand. As a result, large levels of work-in-process (WIP) are necessary between processes to avoid starvation. At Level 2, machines and processes are arranged in departments according to product flow, but unmatched processing rates still necessitate high levels of inventory between departments. At Level 3, the manufacturing system has high speed assembly or transfer lines feeding multiple customers. This configuration still requires high levels of inventory throughout the system to manage the product flow. At Level 4, takt times are defined for groups of customers. Equipment and operators are able to work at the defined takt times; however, there is still some parallel processing in the system. At Level 5, cells and subsystems are running at the takt time as well as most material supply operations. Equipment and operators are able to work at the minimum takt time, and parallel processing has been eliminated. At Level 6, production is balanced to takt time throughout the entire value stream in the manufacturing system. In addition, work-in-process (WIP) has been minimized between processes and cells/subsystems. Finally, the manufacturing system is flexible enough to operate at different takt times because the pace, and therefore volume, of customer demand is fed back throughout the manufacturing system.

5.4.9 FR-T3 'Reduce run size delay'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-T3 'Reduce run size delay' is shown in Figure 5.19.

FR-T3: Reduce run size delay	
1	System is designed to operate based on forecast demand, not actual demand. Production in large run sizes to avoid long setup times.
2	System is designed to operate based on forecast demand, not actual demand. Run size is based on <1 month's forecast demand.
3	System is designed to operate based on forecast demand, not actual demand. Run size is based on <1 week's forecast demand.
4	System is still based on forecast demand. Run size is based on a schedule that repeats on a daily basis. External setup tasks are reduced.
5	System operates based on actual demand, producing exactly what the customer consumes each shift. Internal setup tasks reduced.
6	System produces the actual desired mix and quantity during each demand interval based either on a standard container size or in sequence with customer demand. All setup tasks are minimal.

Figure 5.19: FR-T3 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design reduces run size delay. A manufacturing system should be designed to produce to actual customer demand, not forecasted demand. In order to produce to actual customer demand, run sizes must be decreased. Setup times and setup tasks must be reduced so that different part types can be produced with little to no delay for changeover. Then, a manufacturing system can produce the desired mix and the desired quantity of products during each demand interval, which may be as short as one day, one shift, or even only a few hours.

5.4.10 FR-T4 'Reduce transportation delay'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-T4 'Reduce transportation delay' is shown in Figure 5.20.

FR-T4: Reduce transportation delay	
1	Departmental layout with machines arranged by function in isolated departments (job shop type). Complex material flow.
2	Departmental, process-focused layout grouped to reflect value stream sequence of operations. Parallel processing occurs. Routing is unclear.
3	Product or customer-oriented material flow with machines/stations in assembly/transfer line layout. Parallel processing still exists.
4	Cellular layout with machines/stations close together. Some batch processes/monument machines complicate material flow.
5	Cellular design/material flow-oriented layout applies throughout value stream. Material supply designed to reduce transportation.
6	In addition to Level 5, reduced transportation throughout supply chain. Production near customer and supplier base. Material supply designed to replenish at fixed intervals.

Figure 5.20: FR-T4 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design reduces transportation delay. The layout of a manufacturing system should be driven by the material flow of the products. In addition, parallel processing and large monument machines should be avoided because they complicate the flow through the system. A cellular layout with machines and stations close together is one possible solution to reduce transportation delay. The ultimate goal is to design a material flow-oriented layout throughout the value stream within the manufacturing system and throughout the entire supply chain from the suppliers to the final customers.

5.4.11 FR-T5 'Reduce systematic operational delays'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-T5 'Reduce systematic operational delays' is shown in Figure 5.21.

FR-T5: Reduce systematic operational delays	
1	Routine tasks, such as material handling, chip removal, and machine maintenance, interrupt production frequently.
2	Routine tasks are designed so that they may be done infrequently, such as loading lots of material, large chip reservoirs, and infrequent maintenance.
3	Some routine tasks are scheduled to be done after hours. Production still must stop regularly for other activities (i.e. material supply).
4	Machines/processes designed so they do not have to be interrupted for routine material replenishment, chip removal, and machine maintenance.
5	Machines/processes designed so they rarely ever stop for routine activities.
6	In addition to Level 5, operators continually make improvements in eliminating interferences between production workers, material handling, maintenance, etc.

Figure 5.21: FR-T5 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design reduces systematic operational delays. Routine activities necessary in a manufacturing system should not interrupt production. These routine tasks include material handling, equipment maintenance, chip removal from machines, and work preparation, among other necessary but non-value-adding tasks. Machines and stations should be designed such that these routine activities can be completed without interrupting production. As always, continuous improvements should be made to eliminate all interferences which halt production.

5.4.12 FR-D1 'Eliminate operators' waiting on machines'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-D1 'Eliminate operators' waiting on machines' is shown in Figure 5.22.

FR-D1: Eliminate operators' waiting on machines	
1	One person, one machine design. Operator watches machine run.
2	One person, one machine design. Operator waits on machine when running, or does "fill-in" work when available.
3	Operator runs more than one machine of the same type of manufacturing process. Machines do not have self-stopping capability.
4	Operator runs many different types of machines with self-stopping capability. No operator-process work routine is defined.
5	Multi-skilled operator runs several machines/ processes with self-stopping capability at takt time. An operator-process work routine is followed.
6	The operator-process work routine is continuously improved and updated by operators. Number of operators may be varied to achieve a range of takt times.

Figure 5.22: FR-D1 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design eliminates operators' waiting on machines. Operators should not wait at a machine and watch it run its cycle. Operators should be multi-skilled to run multiple machines of different types. Machines should be designed to run autonomously upon operator instruction and should have self-stopping capability. An operator-process work routine must be documented and used so that operators follow a defined sequence of operations which repeats each takt time. Finally, the number of operators can be varied so that a range of takt times can be achieved to meet varying customer demand.

5.4.13 FR-D2 'Eliminate wasted motion of operators'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-D2 'Eliminate wasted motion of operators' is shown in Figure 5.23.

FR-D2: Eliminate wasted motion of operators	
1	Excessive walking required to perform work tasks and to search for tools and materials. Work stations are not designed ergonomically.
2	Unnecessary walking has been somewhat reduced due to product flow-oriented layout, but all ergonomic problems still remain.
3	Workers isolated to stations to avoid walking. Some tools and materials are available at the point of use. Ergonomic problems still remain.
4	5S program implemented so that parts, tools and equipment are where they are required. Some improvements in ergonomics are made.
5	5S program continually eliminates wasted motion and improves ergonomics. Machines are small and close together to reduce walking distances.
6	Level 5 applied throughout the value stream, and 5S program is understood by all employees and applied beyond the shop floor.

Figure 5.23: FR-D2 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design eliminates wasted motion of the operators. Operators should not have to search for tools and materials during their work sequence. A maintenance program, such as 5S [Monden, 1998], can help make sure that all tools, materials, and equipment are available to the operators when they are required. In addition, work stations should be designed ergonomically, and machines should be close together to reduce unnecessary walking.

5.4.14 FR-I1 'Improve effectiveness of production managers'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-I1 'Improve effectiveness of production managers' is shown in Figure 5.24.

FR-I1: Improve effectiveness of production managers	
1	Vertical organization with many levels of management. Changes are slow to implement as they require authorization from many people.
2	Management and support groups organized by function. Changes are slow to implement as they require authorization from many people.
3	Management still organized by function, but some support groups organized by product (IPT). Team members evaluated by function, not product.
4	Support groups dedicated to products. Work teams formed on the shop floor are evaluated based on the products.
5	System design enables work teams to track their performance. Work teams are responsible for their performance.
6	System design applied throughout the value stream enables work teams and support groups to track and improve their performance.

Figure 5.24: FR-I1 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design improves the effectiveness of the production managers. Vertically organized management according to function is typically slow to implement changes and very inflexible. Therefore, horizontal organization according to products and a manufacturing system design which enables self-directed work teams is preferable. These work teams should be responsible for certain products, and the teams should monitor and improve their performance constantly.

5.4.15 FR-I2 'Eliminate information disruptions'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR-I2 'Eliminate information disruptions' is shown in Figure 5.25.

FR-I2: Eliminate information disruptions	
1	No information system is used so it is difficult to understand the production status.
2	An information system (e.g. MRP) is used, but employees do not understand or trust it because it is constantly erroneous or out of date.
3	An information system is used to plan and schedule production, but it requires a team of expeditors and constant rescheduling to control production.
4	A visual information system is used, but some employees do not understand how the visual system represents the production status.
5	A visual information system is used, and all employees understand how to use the visual information system.
6	A visual information system provides constant feedback about the production status, and employees react quickly and effectively to any abnormalities in the system.

Figure 5.25: FR-I2 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design eliminates information disruptions. The information system to plan and schedule a manufacturing system is very important to the operation of the system. A standard system for visual management should be put in place, which all managers and operators can understand and use. A visual information system which all can understand will result in a more responsive and flexible manufacturing system.

5.4.16 FR 13 'Minimize investment over production system lifecycle'

The column of the MSD Evaluation Tool which assesses the satisfaction of FR 13 'Minimize investment over production system lifecycle' is shown in Figure 5.26.

FR 13: Minimize investment over production system lifecycle	
1	Dedicated machines are designed to run as fast as possible. Flexibility for future design and volume changes are not considered.
2	High speed, batch production, dedicated machines enable development of lower cost tools and fixtures.
3	Machines are reconfigurable for different part types, but they are not designed to run at a defined takt time in product-oriented flow layouts.
4	Several machines may be operated by one operator in a flow layout but not right-sized and do not run at minimum takt time. CT may be < 30 secs.
5	Machines are designed to run at minimum takt time in a cellular layout. Machines are designed to be product flexible and reusable. CT > 30 secs.
6	Machines are designed, with continually reduced cost and complexity, to run at minimum takt time in a cellular layout. Standard machines may be quickly modified in-house. CT > 30 secs.

Figure 5.26: FR 13 Column of the MSD Evaluation Tool

This column evaluates how well a manufacturing system design minimizes investment over the production system lifecycle. Machines should be simple and flexible so that they can be used for different product types and future product models. Equipment should also be designed ergonomically so operators do not waste much of their time on non-value-adding tasks. Furthermore, machines should have cycle times greater than thirty seconds in order to match the operator cycle times. Machines with longer cycle times are usually simpler and less expensive, and the longer cycle times sometimes reduce the forces necessary during processing, prolonging the life of the machines.

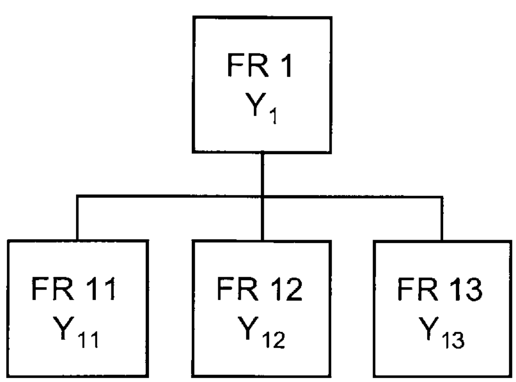
Finally, machines and equipment should be designed to run at a minimum takt time in order to accommodate varying customer demand.

5.5 Interaction of Requirements

In an attempt to perform a design evaluation, one additional issue which must be addressed is how assessments of one FR impact parent or sibling FRs. Each FR can be given a score, labeled Y_i, which is an evaluation of how well an FR is satisfied by the system design. This score may affect parent FRs, or it may affect sibling FRs.

5.5.1 Relationship between Parent and Children FRs

Figure 5.27 depicts the relation between the achievement of FRs to a parent FR. FR 1 (parent FR) is satisfied by DP 1 and is further decomposed into the FRs 11, 12 and 13 (children FRs). It can then be said that FR 1 is fully satisfied when the decomposed FRs are satisfied, and its score is a function of the decomposed FRs' scores as shown by the equations in Figure 5.27. Depending on their relative importance, each lower level FR will have a different weighting factor associated with it, as in the concept selection algorithm. The fact that upper level scores are dependent upon lower level scores suggests that the evaluation will be carried out in a bottom-up approach.

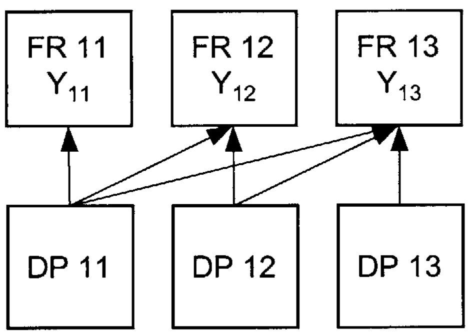


$$Y_1 = f(Y_{11}, Y_{12}, Y_{13})$$
$$Y_i = f(Y_{i,1}, Y_{i,2}, \ldots, Y_{i,j})$$

Figure 5.27: Relationship of Scores between Parent and Children FRs

5.5.2 Relationship between Sibling FRs

The satisfaction, or score, of an FR is also dependent upon how well sibling FRs are satisfied, if sibling DPs impact the FR being evaluated. This condition is depicted in Figure 5.28 along with the equations. If DPs 11 and 12 have an impact on FR 13, then FR 13's score will be a function of the scores of FRs 11 and 12. Again, the weightings (which may be negative if the DPs impact the FR negatively) are determined based on their relative importance and impact on each FR. In addition to the fact that the evaluation proceeds bottom-up, it is also path-dependent within a single level according to the Design Matrix. However, this fact is true only for decoupled designs; uncoupled designs are path-independent, and coupled designs provide no clear path for evaluation.



$$Y_{13} \geq f(Y_{11}, Y_{12})$$

$$Y_{12} \geq f(Y_{11})$$

$$Y_{ij} \geq f(Y_{i,1},\ldots,Y_{i,j-1},Y_{i,j+1},\ldots,Y_{i,n})[DM],_{j\neq 1, j\neq n}$$

$$Y_{ij} \geq f(Y_{i,j+1},\ldots,Y_{i,n})[DM],_{j=1}$$

$$Y_{ij} \geq f(Y_{i,1},\ldots,Y_{i,j-1})[DM],_{j=n}$$

Figure 5.28: Relationship of Scores between Sibling FRs

Given the structure of Axiomatic Design, the relationships established in the MSD Decomposition and Design Matrices provide a simple mechanism for determining the impact of FR scores upon each other in a bottom-up and path-dependent approach.

Chapter 6: Applications

6.1 Introduction to Applications of the MSD Evaluation Tool and Key Performance Measurements of the MSD Decomposition

Many manufacturing system design projects have been undertaken by members of the MIT Production System Design Laboratory in the automotive industry. These projects have involved several different manufacturing plants: Coclisa Climate Control Systems Plant, Indianapolis Steering Systems Plant, Monroe Chassis Components and Systems Plant, and Sterling Heights Axle and Driveline Systems Plant. The products which have been affected by each of these projects include hoses, rack and pinion steering gears, catalytic converters, and axles.

For each of these manufacturing system design projects, this chapter examines either an existing assembly line which was converted to an assembly cell or a new assembly cell which was designed for a new product line. The members on each of the projects used the Manufacturing System Design Decomposition (MSDD) to guide their efforts at the plants. Each of the projects showed varying levels of success upon completion, but they all showed definite improvements over the existing manufacturing systems at the plants. Only general information about the actual conversion and/or design process for each manufacturing plant is included because the aim of this chapter is not to discuss the details of manufacturing system design.

The goal of this chapter is to investigate how successful each of these projects have been by applying the Manufacturing System Design Evaluation Tool (MSDET) and the key performance measurements (PMs) discussed in previous chapters to each project. The MSD Evaluation Tool was applied both to the existing manufacturing system and to the newly designed manufacturing system for each plant. Similarly, the key performance measurements were applied both to the existing system and to the newly designed system as well. In this way, the projects could be evaluated based on the improvements made over the existing manufacturing systems. The usefulness and effectiveness of both the MSD Evaluation Tool and the key performance measurements in assessing the design and performance of manufacturing system designs will be shown in the remainder of this chapter.

The MSD Evaluation Tool images used in this chapter have been slightly altered. The pie charts used for qualitative scoring have been enlarged for greater visibility. An example image is shown in Figure 6.1 with all pie charts empty.

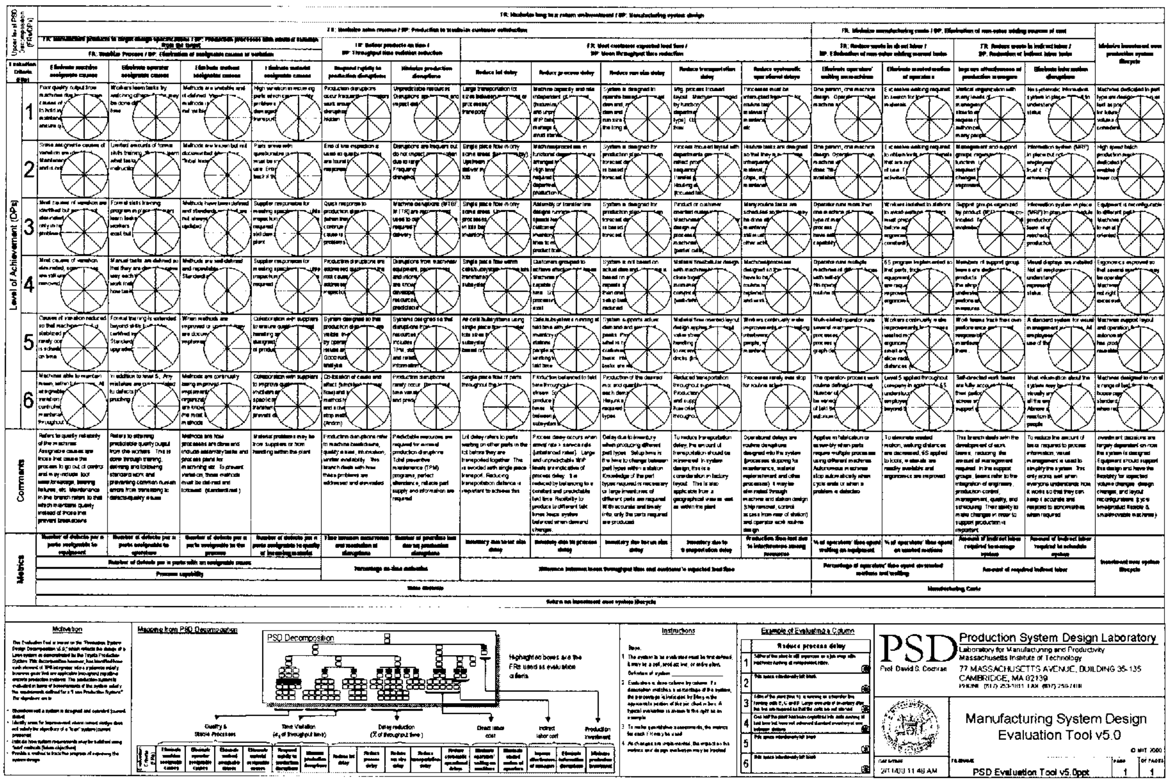


Figure 6.1: MSD Evaluation Tool with Enlarged Pie Charts for Scoring

In addition, a Performance Measurements Worksheet has been created which includes all of the key performance measurements for each project. An example image is shown in Figure 6.2 with all fields empty.

Performance Measurements Worksheet - Plant Name				
	State of the Manufacturing System		Normalized Comparison	
	Before - Mass	After - Lean		
Brief Description of the Manufacturing System			After - Lean	Before - Mass
Production volume per day				
Number of shifts per day				
Production pieces per hour				
Line cycle time or Takt time				
Work in process				
Inventory (number of parts)				
Floor space consumed				
Total distance parts travel				
Average number of defects per month				
Number of direct workers				
Operator hours required per part				
Percent operators' time doing NVA work*				
Percent operators' time for NVA movement*				
Overtime required per day				
Percent absenteeism per month				
Number of indirect workers required to manage and schedule the system				
Customer expected lead time				
Throughput time of system				
Material replenishment rate				
FTT (First time through)				
Production time lost due to disruptions				
Percent on-time deliveries				
Notes:				
* NVA work refers to non-value adding manual tasks				
* NVA movement refers to non-value adding walking, searching for tools, parts, etc.				

Figure 6.2: Performance Measurements Worksheet with All Fields Empty

The first column of this worksheet lists the key performance measurements. The second column is for the PMs of the existing manufacturing system at the plant. The third column is for the PMs of the newly designed manufacturing system for each project. Because it is difficult to attain data for all of these performance measures, some of the fields may remain empty for some projects, but all fields for which data is available have been filled in.

Because the text in Figure 6.1 is not legible, the columns of the MSD Evaluation Tool are presented individually here in Figure 6.3 for reference throughout the remainder of this chapter.

FR-Q11: Eliminate machine assignable causes	
1	Unknown causes of variation lead to poor quality output from machines (unable to hold mean). No maintenance to ensure quality.
2	Some causes of variation are identified but not eliminated. Maintenance is occasional but not scheduled.
3	Most causes of variation are identified but still not eliminated. Maintenance is only in response to quality problems.
4	Most causes of variation are eliminated, but some causes still cannot be eliminated. Maintenance is scheduled but infrequent.
5	Causes of variation eliminated so that mean shifts in machine output rarely occur. Maintenance is scheduled regularly and performed on time.
6	All machine assignable causes of variation eliminated or controlled through a regular, continuous maintenance program throughout system.

FR-Q12: Eliminate operator assignable causes	
1	Workers learn tasks by watching others. Tasks are completed differently each time.
2	Workers learn tasks from instructions and receive a limited amount of formal skills training. Work methods still vary among workers.
3	Workers learn tasks from senior workers. Formal skills training program in place. Work standards exist but methods still vary.
4	Formal skills training program is followed. Standard work instructions define methods so they are done the same way each time.
5	Formal training is extended beyond skills to OJT by certified instructors. Standards are followed and improved by workers.
6	In addition to Level 5, mistakes are not translated to defects through the use of mistake proofing (poka-yokes)

FR-Q13: Eliminate method assignable causes	
1	Methods are unstable and ill-defined. Variation in methods is arbitrary and is not visible.
2	Methods are known but not documented (shop floor "tribal knowledge").
3	Methods have been defined, but they are not always followed.
4	Methods are well-defined and repeatable, and they are standardized and followed.
5	Methods are well-defined and followed, and they are updated with improvements, which are then implemented.
6	Methods are continually being improved and implemented throughout the organization. All employees are knowledgeable about the most current methods.

FR-Q14: Eliminate material assignable causes	
1	High variation in incoming parts cause quality problems. Materials are damaged in storage and transport.
2	Parts arrive with questionable quality and must be inspected before use. Entire lots are sent back if there are bad parts.
3	Supplier responsible for meeting specifications. Little inspection of incoming parts required. Some parts are still damaged within the plant.
4	Supplier responsible for meeting specifications. Little inspection of incoming parts required. Only a few parts are still damaged within the plant.
5	Collaboration with suppliers to ensure quality. Material handling containers designed to maintain quality of products.
6	Collaboration with suppliers to continuously improve quality of the incoming parts. Suppliers are involved in developing specifications for parts.

FR-R1: Respond rapidly to production disruptions	
1	Production disruptions occur frequently. Operators work around these disruptions so they are hidden.
2	Production disruptions occur frequently, but end of line inspection is used to find quality problems, resulting in slow response to problems.
3	Production disruptions, when they are identified, are addressed quickly. Root cause is not eliminated so problems may reoccur.
4	Production disruptions are identified by in-process inspection and addressed quickly. Root cause is eventually addressed.
5	System designed so that production disruptions are visible. In-process checks so operators find quality issues quickly. Good root cause analysis.
6	In addition to Level 5, systematic method in use for communicating and solving problems. Line stop methods in use (andon).

FR-P1: Minimize production disruptions	
1	Disruptions due to unpredictable resources are frequent and impact delivery.
2	Disruptions due to unpredictable resources are still frequent, but large buffer sizes reduce impact on delivery. No knowledge of type of disruptions.
3	Machine disruptions (MTBF, MTTR) are recorded and used to determine lead time required for delivery.
4	Disruptions from equipment, people, parts and information availability are known on a delayed basis and used to determine lead time.
5	All disruptions reduced through system design including perfect attendance, TPM, std. material supply, information feedback system.
6	Production disruptions rarely occur. Information system in place to immediately identify production disruptions and communicate problems to the correct support resources.

FR-T1: Reduce lot delay	
1	Large transportation lot sizes between machines or processes to reduce transportation costs.
2	Large transportation lot sizes between machines or processes to reduce transportation costs although machines are arranged in product flow.
3	Single piece flow in only some areas. Upstream processes still deliver materials in large lots.
4	Single piece flow within some cells/subsystems. Large lots transferred between subsystems.
5	Single piece flow within all cells/subsystems. Lot sizes transferred between subsystems are being reduced.
6	Single piece flow of parts throughout the factory, both within cells/subsystems and between subsystems.

FR-T2: Reduce process delay	
1	Machine capacity and rate independent of takt time. Large, unpredictable WIP levels exist between departments to avoid system starvation.
2	Machines/processes arranged in functional departments for product flow. Large, unpredictable WIP levels still exist between departments.
3	Assembly/transfer lines run at high speeds. Large inventories are necessary before and after lines to meet aggregate demand of many customers.
4	Customers grouped to achieve desired takt times. Machines/people are capable of operating at takt time. Some parallel processing still exists.
5	Cells/subsystems operate at takt time, including machines and people. Materials are supplied in most areas at takt time. No parallel processing.
6	Production balanced to takt time throughout entire value stream. Flexibility to produce at different takt times. Pace of customer demand fed back throughout manufacturing system.

FR-T3: Reduce run size delay	
1	System is designed to operate based on forecast demand, not actual demand. Production in large run sizes to avoid long setup times.
2	System is designed to operate based on forecast demand, not actual demand. Run size is based on <1 month's forecast demand.
3	System is designed to operate based on forecast demand, not actual demand. Run size is based on <1 week's forecast demand.
4	System is still based on forecast demand. Run size is based on a schedule that repeats on a daily basis. External setup tasks are reduced.
5	System operates based on actual demand, producing exactly what the customer consumes each shift. Internal setup tasks reduced.
6	System produces the actual desired mix and quantity during each demand interval based either on a standard container size or in sequence with customer demand. All setup tasks are minimal.

FR-T4: Reduce transportation delay	
1	Departmental layout with machines arranged by function in isolated departments (job shop type). Complex material flow.
2	Departmental, process-focused layout grouped to reflect value stream sequence of operations. Parallel processing occurs. Routing is unclear.
3	Product or customer-oriented material flow with machines/stations in assembly/transfer line layout. Parallel processing still exists.
4	Cellular layout with machines/stations close together. Some batch processes/monument machines complicate material flow.
5	Cellular design/material flow-oriented layout applies throughout value stream. Material supply designed to reduce transportation.
6	In addition to Level 5, reduced transportation throughout supply chain. Production near customer and supplier base. Material supply designed to replenish at fixed intervals.

FR-T5: Reduce systematic operational delays	
1	Routine tasks, such as material handling, chip removal, and machine maintenance, interrupt production frequently.
2	Routine tasks are designed so that they may be done infrequently, such as loading lots of material, large chip reservoirs, and infrequent maintenance.
3	Some routine tasks are scheduled to be done after hours. Production still must stop regularly for other activities. (i.e. material supply)
4	Machines/processes designed so they do not have to be interrupted for routine material replenishment, chip removal, and machine maintenance.
5	Machines/processes designed so they rarely ever stop for routine activities.
6	In addition to Level 5, operators continually make improvements in eliminating interferences between production workers, material handling, maintenance, etc.

FR-D1: Eliminate operators' waiting on machines	
1	One person, one machine design. Operator watches machine run.
2	One person, one machine design. Operator waits on machine when running, or does "fill-in" work when available.
3	Operator runs more than one machine of the same type of manufacturing process. Machines do not have self-stopping capability.
4	Operator runs many different types of machines with self-stopping capability. No operator-process work routine is defined.
5	Multi-skilled operator runs several machines/ processes with self-stopping capability at takt time. An operator-process work routine is followed.
6	The operator-process work routine is continuously improved and updated by operators. Number of operators may be varied to achieve a range of takt times.

	FR-D2: Eliminate wasted motion of operators
1	Excessive walking required to perform work tasks and to search for tools and materials. Work stations are not designed ergonomically.
2	Unnecessary walking has been somewhat reduced due to product flow-oriented layout, but all ergonomic problems still remain.
3	Workers isolated to stations to avoid walking. Some tools and materials are available at the point of use. Ergonomic problems still remain.
4	5S program implemented so that parts, tools and equipment are where they are required. Some improvements in ergonomics are made.
5	5S program continually eliminates wasted motion and improves ergonomics. Machines are small and close together to reduce walking distances.
6	Level 5 applied throughout the value stream, and 5S program is understood by all employees and applied beyond the shop floor.

	FR-I1: Improve effectiveness of production managers
1	Vertical organization with many levels of management. Changes are slow to implement as they require authorization from many people.
2	Management and support groups organized by function. Changes are slow to implement as they require authorization from many people.
3	Management still organized by function, but some support groups organized by product (IPT). Team members evaluated by function, not product.
4	Support groups dedicated to products. Work teams formed on the shop floor are evaluated based on the products.
5	System design enables work teams to track their performance. Work teams are responsible for their performance.
6	System design applied throughout the value stream enables work teams and support groups to track and improve their performance.

	FR-I2: Eliminate information disruptions
1	No information system is used so it is difficult to understand the production status.
2	An information system (e.g. MRP) is used, but employees do not understand or trust it because it is constantly erroneous or out of date.
3	An information system is used to plan and schedule production, but it requires a team of expeditors and constant rescheduling to control production.
4	A visual information system is used, but some employees do not understand how the visual system represents the production status.
5	A visual information system is used, and all employees understand how to use the visual information system.
6	A visual information system provides constant feedback about the production status, and employees react quickly and effectively to any abnormalities in the system.

	FR 13: Minimize investment over production system lifecycle
1	Dedicated machines are designed to run as fast as possible. Flexibility for future design and volume changes are not considered.
2	High speed, batch production, dedicated machines enable development of lower cost tools and fixtures.
3	Machines are reconfigurable for different part types, but they are not designed to run at a defined takt time in product-oriented flow layouts.
4	Several machines may be operated by one operator in a flow layout but not right-sized and do not run at minimum takt time. CT may be <30 secs.
5	Machines are designed to run at minimum takt time in a cellular layout. Machines are designed to be product flexible and reusable. CT>30 secs.
6	Machines are designed, with continually reduced cost and complexity, to run at minimum takt time in a cellular layout. Standard machines may be quickly modified in-house. CT>30 secs.

Figure 6.3 Columns of the MSD Evaluation Tool

6.2 Coclisa Climate Control Systems Plant

The Coclisa Plant manufactures several different products for automobiles. These products include radiators, compressors, condensers, and hoses. All of these products are used in automotive climate control systems. Annually, Coclisa manufactures 7 million hose components with 1227 employees. Currently, hose manufacturing occupies 163,000 square feet across three different facilities.

In this project, the existing manufacturing system for hose assembly uses 12 moving assembly lines. These moving assembly lines have been converted into two assembly cells after "lean" implementation, which can produce enough hoses to meet customer demand [Estrada, 2000, and Estrada, Shukla, Cochran, 2000, and Shukla, Estrada, Cochran, 2000].

6.2.1 Application of the MSD Evaluation Tool at Coclisa – Before Using the MSD Decomposition

One of the 12 assembly lines in the existing system for hose assembly at the Coclisa Plant is shown in Figure 6.4. This assembly line is designed to run at a set pace of 380 pieces per hour. Therefore, the throughput time, dictated by the line speed and large amounts of WIP at stations 1-4, is about 20 minutes although it varies due to the high defect rate. Overtime is necessary on a daily basis because customer demand has risen since the assembly lines were first installed. Because of this insufficient capacity, production has been transferred to other plants in order to produce enough parts.

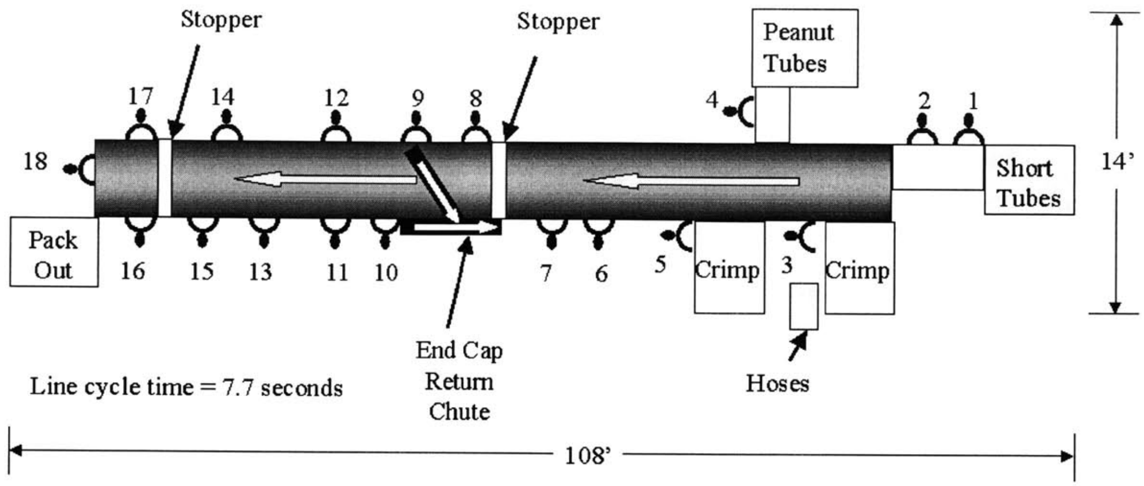


Figure 6.4: Existing Coclisa Assembly Line Layout for Manufacturing Hoses

Operators are tied to individual stations, and all operators must be present regardless of whether the volume of production is 10 parts or 10,000 parts. The operators have no defined, standard work instructions, and roughly 50% of the available production time is spent idle waiting for parts. The moving assembly line makes it difficult to catch defects when they are made, which leads to a very high defect rate.

The MSD Evaluation Tool was applied to the existing hose manufacturing line at the Coclisa Plant, and the evaluation is shown in Figure 6.5. The existing manufacturing system for hoses falls between Levels 1-5, mostly in Levels 2 and 3, and very little of the system rates at or above Level 4.

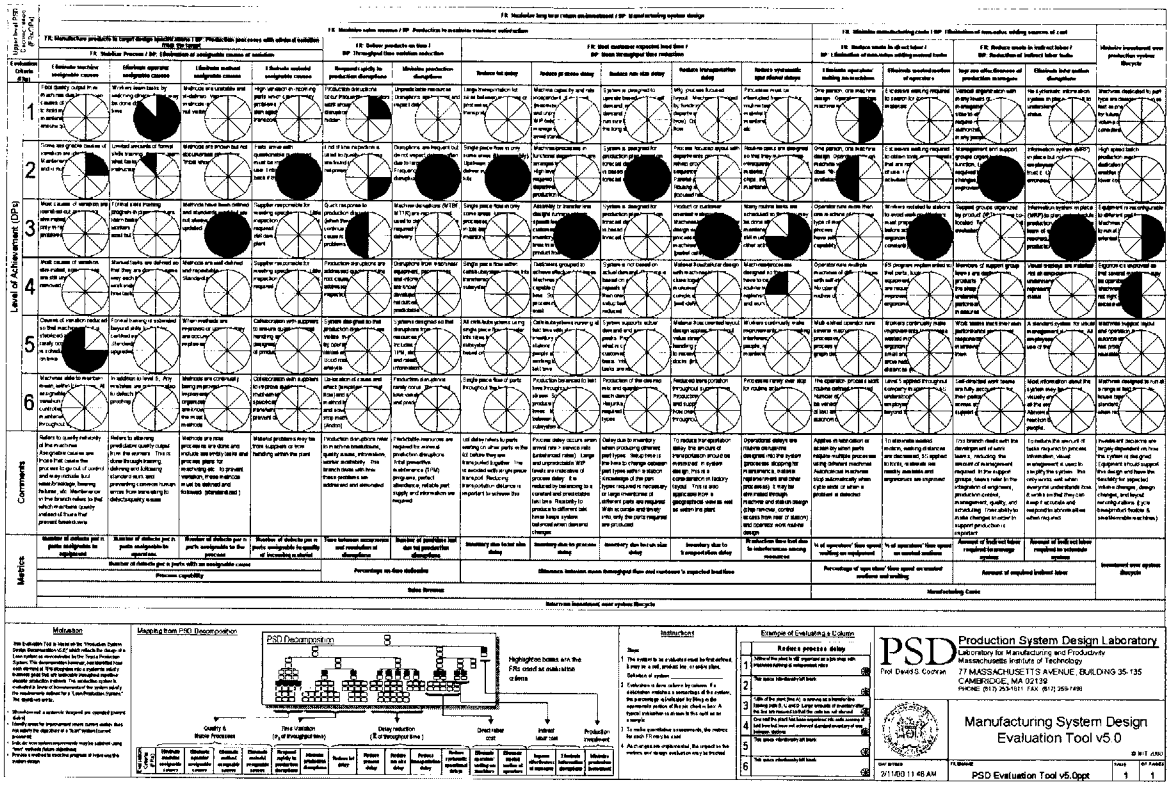


Figure 6.5: MSD Evaluation Tool for the Existing Coclisa Assembly Line for Manufacturing Hoses - Before

Through application of the MSD Evaluation Tool to the existing system at Coclisa, it becomes visually apparent that the entire system can be improved overall, and each column of the MSD Evaluation Tool provides more insight into specific needs for improvement. For example, the worst column for Coclisa is 'Eliminate operate assignable causes,' which is evaluated to be 87.5% at Level 1 and 12.5% at Level 2. Other extremely weak areas of the existing system are 'Eliminate operators' waiting on machines,' 'Respond rapidly to production disruptions,' and five areas which are evaluated to be entirely at Level 2.

6.2.2 Application of the MSD Evaluation Tool at Coclisa – After Using the MSD Decomposition

The newly designed manufacturing system at Coclisa is shown in Figure 6.6. This cellular system design has the flexibility to produce different volumes of hoses, according to varying customer demand. The throughput time is now only 72 seconds, and the volume of production can be varied by changing the number of operators in the cells. Because of this volume flexibility, overtime is no longer necessary in order to meet the customer demand, and production does not have to be spread across several manufacturing plants.

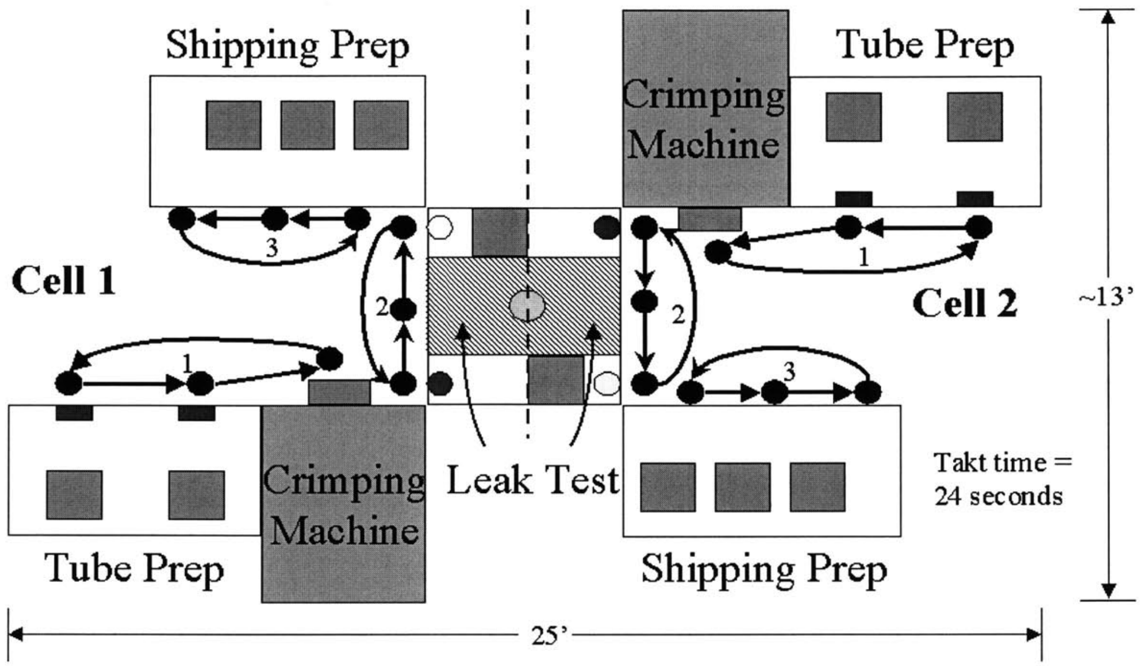


Figure 6.6: New Coclisa Two Assembly Cell Layout for Manufacturing Hoses

Operators are no longer tied to individual work stations and now have defined workloops to operate multiple stations. The operators have defined, standard work instructions, and both ergonomic issues and non-value-adding tasks and motions have largely been eliminated. By implementing single piece flow, passing on only good parts, and modifying the inspection procedures, the defect rate has been dramatically decreased.

After the hose assembly line at the Coclisa Plant was converted to two assembly cells, the MSD Evaluation Tool was again applied to the system, and the evaluation is shown in Figure 6.7. The new manufacturing system design falls between Levels 2-6, mostly in Levels 3-5, and no aspects of the system remain at Level 1.

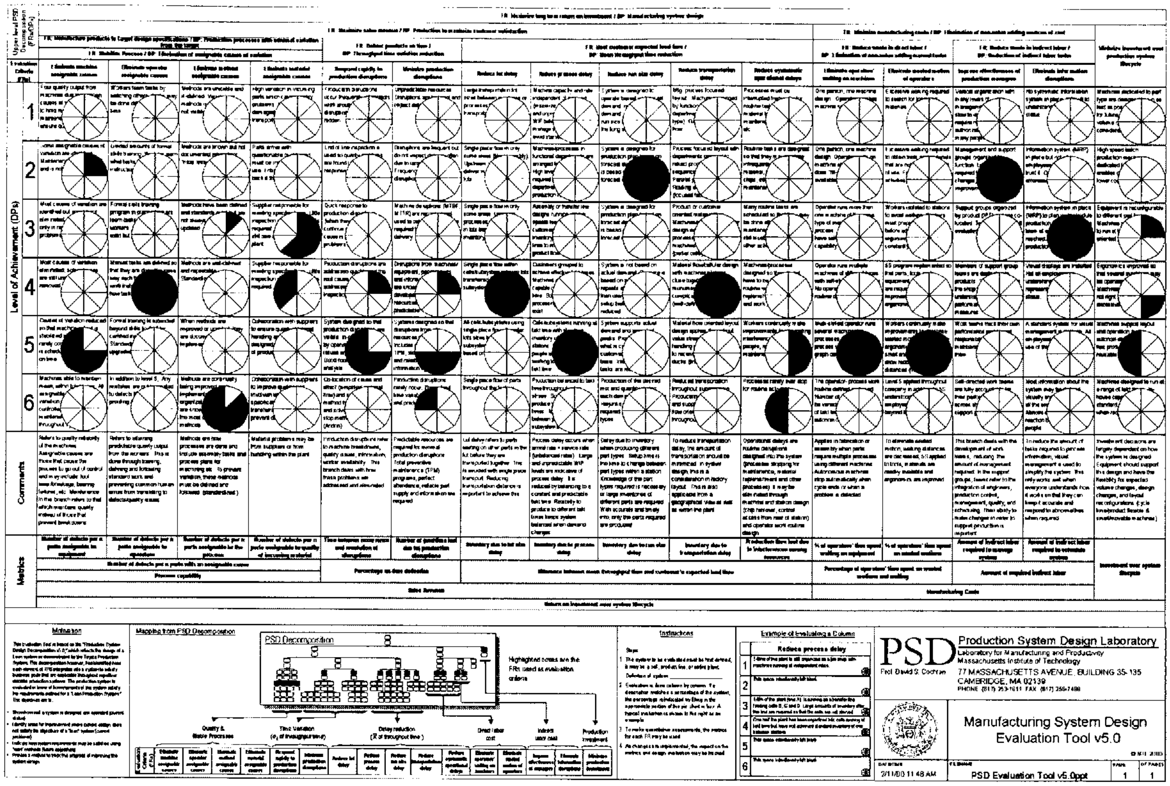


Figure 6.7: MSD Evaluation Tool for the New Coclisa Assembly Cells for Manufacturing Hoses - After

By comparing the applications of the MSD Evaluation Tool to the existing system and new cellular system design at Coclisa, it becomes visually apparent that the entire system design has been improved dramatically, and the two systems can be compared column by column for more specific information about the areas of improvement. For example, 'Eliminate operator assignable causes,' previously the worst column of the evaluation with 87.5% at Level 1 and 12.5% at Level 2, is now entirely at Level 4. The most significant improvements occurred in 'Eliminate method assignable causes,' 'Respond rapidly to production disruptions,' 'Minimize production disruptions,' and 'Eliminate operators' waiting on machines.' 'Eliminate method assignable causes' improved from 100% at Level 3 to an astounding 12.5% at Level 3 and 87.5% at Level 6. 'Respond rapidly to production disruptions' improved from 25% each at Levels 1 and 2 and 50% at Level 3 to a much better 25% at Level 4 and 75% at Level 5. 'Minimize production disruptions' improved from 100% at Level 2 to a greatly improved 25% each at Levels 4 and 6 and 50% at Level 5. Finally, 'Eliminate operators' waiting on machines' improved significantly from 50% each at Levels 1 and 2 to 100% at Level 5. The new system design evaluation shows that nearly all areas of the hose manufacturing system at Coclisa improved, only 4 areas remained the same as the existing system, and no areas of the new manufacturing system design were rated poorer than the existing system. However, having some areas of the evaluation at Level 5 or 6 and other areas at Level 2 or 3 does not indicate a coherent system design. The manufacturing system design can still be improved in all areas, and the MSD Evaluation Tool shows in which areas further improvements can still be made.

6.2.3 Application of Key Performance Measurements at Coclisa

In addition to the MSD Evaluation Tool, key performance measurements were applied to the hose manufacturing system at the Coclisa Plant, and they are shown in Figure 6.8.

Performance Measurements Worksheet - Coclisa				
	State of the Manufacturing System		Normalized Comparison	
	Before - Mass	After - Lean		
Brief Description of the Manufacturing System	Moving Assembly Line	2 Assembly Cells	After - Lean	Before - Mass
Production volume per day	4200	4200	1.00	1.00
Number of shifts per day	1	2	1.00	0.50
Production pieces per hour	470	300	1.00	1.57
Line cycle time or Takt time	7.7 sec	24 sec	1.00	0.32
Work in process	variable (~150)	6 (3 per cell)	1.00	25.00
Inventory (number of parts)	1 day (finished goods)	1 day (finished goods)	1.00	1.00
Floor space consumed	1512 sq. ft.	320 sq. ft.	1.00	4.73
Total distance parts travel	100 ft.	15 ft.	1.00	6.67
Average number of defects per month	226	2.5	1.00	90.40
Number of direct workers	18	12	1.00	1.50
Operator hours required per part	147 sec = .04 hr	82 sec = .02 hr	1.00	1.79
Percent operators' time doing NVA work*	~55%	~33%	1.00	1.67
Percent operators' time for NVA movement*	~70%	~16%	1.00	4.38
Overtime required per day	1 hr	0 hr	1.00	N/A
Percent absenteeism per month	4	0	1.00	N/A
Number of indirect workers required to manage and schedule the system	no change	no change	1.00	1.00
Customer expected lead time	-	-	-	-
Throughput time of system	variable (~20 min)	72 sec	1.00	16.67
Material replenishment rate	variable	50 pcs / 20 min	1.00	N/A
FTT (First time through)	99.70%	100%	1.00	1.00
Production time lost due to disruptions	5-10 hrs/wk	~2 hrs/wk	1.00	3.75
Percent on-time deliveries	-	-	-	-
Notes:				
* NVA work refers to non-value adding manual tasks				
* NVA movement refers to non-value adding walking, searching for tools, parts, etc.				

Figure 6.8: Performance Measurements Worksheet for Coclisa

The comparison of the key performance measurements for the existing, moving assembly line with the new system design of two assembly cells shows that the new system is capable of producing the same volume of parts with the same inventory of finished goods and far less work in process (WIP), only 6 parts compared to the moving assembly line which averages about 150 parts. Moreover, the two assembly cells operate at a reasonable takt time of 24 seconds whereas the existing assembly line has an extremely short cycle time of only 7.7 seconds. The two assembly cells take up only 320 square feet of floorspace instead of 1512 square feet for the assembly line. Also, the parts travel only 15 feet through the new system as opposed to 150 feet in the existing system. The new system design has helped decrease the throughput time to a predictable 72 seconds, much less than the existing system's highly variable 20 minutes. The first time through (FTT) has improved because the number of defects per month has dropped drastically from 226 to only 2.5 parts. Furthermore, the amount of production time lost due to disruptions has decreased from 5-10 hours per week to approximately 2 hours per week. Some of the greatest improvements have been made regarding the operators. Non-value-adding work has been decreased from about 55% to about 33%, and non-value-adding movement has been reduced even more from about 70% to just 16%. This elimination of waste in the operators' tasks has completely eliminated the need for overtime. The application of the key performance measurements to the Coclisa Plant shows that the new system design has far superior performance over the existing system.

6.3 Indianapolis Steering Systems Plant

The Indianapolis Plant manufactures steering components for automobiles. These products include rack and pinion steering gears, rotary valve steering gears, power steering pumps, steering columns, and valve subassemblies. Indianapolis employs about 3000 employees. The manufacturing facility occupies 2 million square feet.

Two different projects at Indianapolis will be presented for two different steering gear manufacturing systems: DEW98 and U222. Each of these new manufacturing systems are assembly cells, and they are compared to the existing WIN88 asynchronous assembly line. The DEW98 and U222 projects will be discussed separately [Cochran, Dobbs, 1999, and Gomez, 2000].

6.3.1 Application of the MSD Evaluation Tool at Indianapolis WIN88 – Before Using the MSD Decomposition

The existing WIN88 manufacturing system for steering gears at the Indianapolis Plant is shown in Figure 6.9. This manufacturing system is a very large asynchronous assembly line. There are about 50 work stations in this line, which do not have balanced cycle times to each other. Also, repair loops are built into the assembly line, and functional testing is a parallel processing operation. Because of the multiple loops in the assembly line layout, the material flow is very complicated. As a result, the throughput time is approximately 46 hours, including machining, with large variation. Large amounts of inventory and work in process (WIP) can be found in many locations throughout this system.

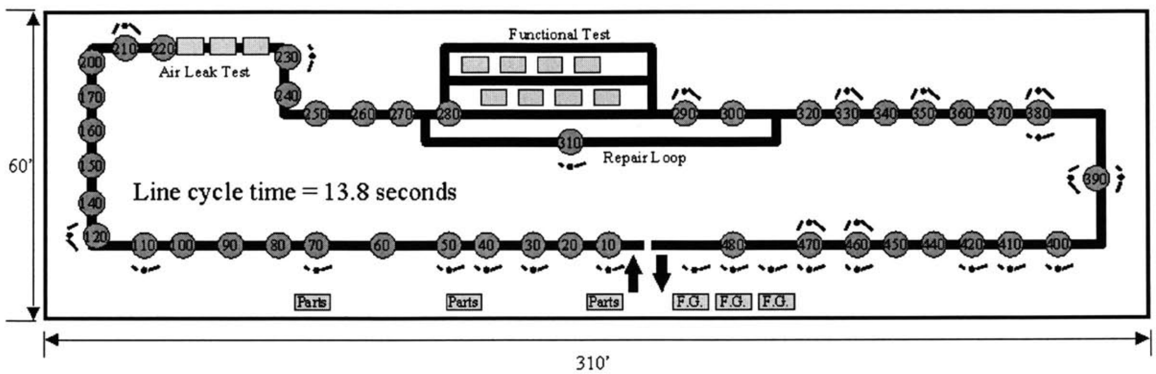


Figure 6.9: Existing Indianapolis WIN88 Asynchronous Assembly Line Layout for Manufacturing Steering Gears

Operators are tied to individual machines or stations with very short cycle times, and some stations are completely automatic. The operators have no defined, standard work instructions, and there are many ergonomic problems and non-value-adding tasks and motions. Quality problems are not traceable to their source in this assembly line. Because the repair loop is built into the line, it is very difficult to identify and eliminate defects and their root causes.

The MSD Evaluation Tool was applied to the existing WIN88 manufacturing system for steering gears at the Indianapolis Plant, and the evaluation is shown in Figure 6.10. The existing manufacturing system falls between Levels 1-4, mostly in Levels 1-3, and virtually none of the system rates at or above Level 4.

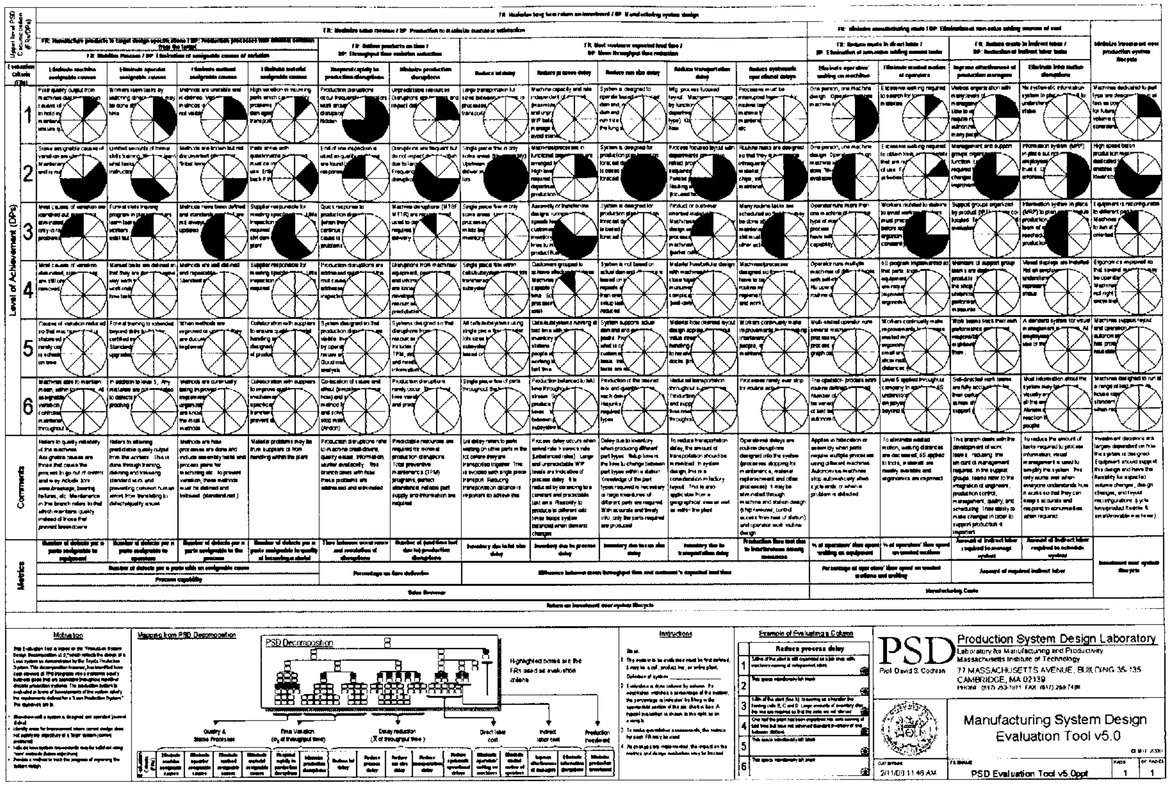


Figure 6.10: MSD Evaluation Tool for the Existing Indianapolis WIN88 Asynchronous Assembly Line for Manufacturing Steering Gears - Before

Through application of the MSD Evaluation Tool to the existing WIN88 manufacturing system for steering gears at Indianapolis, it becomes visually apparent that the entire system can be improved overall, and each column of the MSD Evaluation Tool provides more insight into specific needs for improvement. For example, the worst column for Indianapolis is 'Respond rapidly to production disruptions,' which is evaluated to be 75% at Level 1 and 25% at Level 2. Other extremely weak areas of the existing system are 'Eliminate operators' waiting on machines,' 'Improve effectiveness of production managers,' 'Reduce lot delay,' and 'Reduce process delay.'

6.3.2 Application of the MSD Evaluation Tool at Indianapolis DEW98 – After Using the MSD Decomposition

The newly designed DEW98 manufacturing system for steering gears at Indianapolis is shown in Figure 6.11. This manufacturing system design is an assembly cell operating at a defined takt time. All operations are balanced to the takt time, and there are no integrated repair loops or parallel processing operations to complicate the material flow. However, there is one operator outside of the cell, who is tied to a single work station. As a result, the throughput time is a very predictable 42 minutes, instead of 46 hours. In addition, inventory and work in process (WIP) levels have been reduced and standardized so that they may be visually controlled throughout the system.

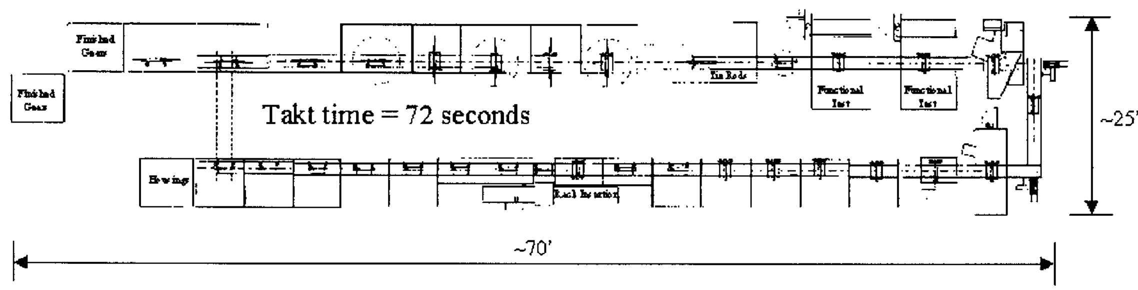


Figure 6.11: New Indianapolis DEW98 Assembly Cell Layout for Manufacturing Steering Gears

Operators now have defined workloops to operate multiple work stations as well as standard work instructions, which have mostly eliminated both ergonomic issues and non-value-adding tasks and motions in the work stations. The number of operators in the assembly cell can be varied in order to achieve volume flexibility. Some quality problems have been eliminated, but there are still many quality issues, particularly with incoming parts from machining. The root causes of these quality problems have not been eliminated in this system.

After designing the new DEW98 manufacturing system for steering gears at the Indianapolis Plant, the MSD Evaluation Tool was again applied to the system, and the evaluation is shown in Figure 6.12. The new manufacturing system design falls mostly in Levels 3 and 4, and very little of the system rates at or below Level 2.

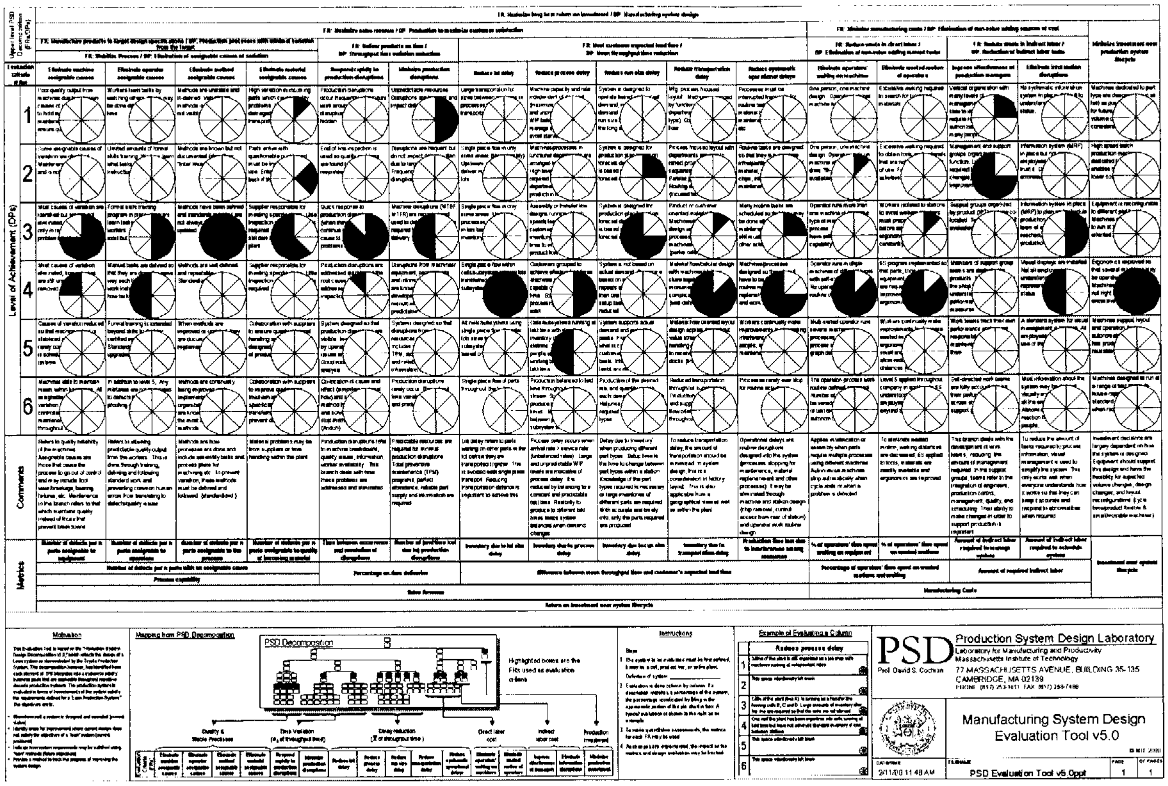


Figure 6.12: MSD Evaluation Tool for the New Indianapolis DEW98 Assembly Cell for Manufacturing Steering Gears - After

By comparing the applications of the MSD Evaluation Tool to the WIN88 asynchronous assembly line and the DEW98 assembly cell at Indianapolis, it becomes visually apparent that the entire system design has been improved dramatically, and the two systems can be compared column by column for more specific information about the areas of improvement. For example, 'Respond rapidly to production disruptions,' previously the worst column of the evaluation with 75% at Level 1 and 25% at Level 2, is now 87.5% at Level 3 and 12.5% at Level 4. The most significant improvements occurred in 'Reduce lot delay,' 'Eliminate operators' waiting on machines,' and 'Minimize investment over production system lifecycle.' 'Reduce lot delay' improved from 100% at Level 2 to 100% at Level 4. 'Eliminate operators' waiting on machines' improved from 50% each at Levels 1 and 2 to a much better 12.5% at Level 2 and 87.5% at Level 4. 'Minimize investment over production system lifecycle' improved from 25% at Level 1, 62.5% at Level 2, and 12.5% at Level 3 to a significantly better 100% at Level 4. The new system design evaluation shows that nearly all areas of the manufacturing system at Indianapolis improved, only 3 areas remained the same as the existing system, and no areas of the new DEW98 manufacturing system design for steering gears were rated poorer than the existing WIN88 manufacturing system. However, the system design can still be improved in all areas, and the MSD Evaluation Tool shows in which areas further improvements can still be made.

6.3.3 Application of Key Performance Measurements at Indianapolis DEW98

In addition to the MSD Evaluation Tool, key performance measurements were applied to the WIN88 and DEW98 manufacturing systems for steering gears at the Indianapolis Plant, and they are shown in Figure 6.13.

Performance Measurements Worksheet - Indy DEW98				
	State of the Manufacturing System		Normalized Comparison	
	Before - Mass	After - Lean		
Brief Description of the Manufacturing System	WIN88 Asynchronous Assembly Line	DEW98 Assembly Cell	**After - Lean**	**Before - Mass**
Production volume per day	3800	600	1.00	6.33
Number of shifts per day	2	2	1.00	1.00
Production pieces per hour	260	50	1.00	5.20
Line cycle time or Takt time	13.8 sec	72 sec	1.00	0.19
Work in process	270	30	1.00	9.00
Inventory (number of parts)	13000 (finished goods)	~3000 (finished goods)	1.00	4.33
Floor space consumed	20000 sq. ft.	1750 sq. ft.	1.00	11.43
Total distance parts travel	720 ft.	250 ft.	1.00	2.88
Average number of defects per month	~285 / day	30-40 / day	1.00	8.14
Number of direct workers	32	10	1.00	3.20
Operator hours required per part	12.3 min	13 min	1.00	0.95
Percent operators' time doing NVA work*	35%	25%	1.00	1.40
Percent operators' time for NVA movement*	30%	25%	1.00	1.20
Overtime required per day	2 hr	2 hr	1.00	1.00
Percent absenteeism per month	12%	12%	1.00	1.00
Number of indirect workers required to manage and schedule the system	1.14	1.14	1.00	1.00
Customer expected lead time	-	-	-	-
Throughput time of system	46 hr	42 min	1.00	65.71
Material replenishment rate	unpredictable	2 hr	1.00	N/A
FTT (First time through)	85%	90%	1.00	0.94
Production time lost due to disruptions	16 min/hr	24 min/hr	1.00	0.67
Percent on-time deliveries	-	-	-	-
Additional Performance Measurements				
Support personnel (excl. mgmt. & super.)	7	2	1.00	3.50
Repair personnel	3	1	1.00	3.00
Number of models	5	2	1.00	2.50
Notes:				
* NVA work refers to non-value adding manual tasks				
* NVA movement refers to non-value adding walking, searching for tools, parts, etc.				

Figure 6.13: Performance Measurements Worksheet for Indianapolis DEW98

The comparison of the key performance measurements for the existing system of an asynchronous assembly line with the new system design for an assembly cell is not based on equivalent volume of production because the WIN88 and DEW98 systems produce different product models of steering gears; the DEW98 assembly cell does not replace the WIN88 assembly line. However, the comparison shows that the new system is capable of meeting customer demand with far less work in process (WIP) and finished goods inventory. Moreover, the assembly cell operates at a reasonable takt time of 72 seconds whereas the existing assembly line has an extremely short cycle time of only 13.8 seconds. The new assembly cell also takes up much less floorspace, only 3000 square feet instead of 20,000 square feet. Also, the parts travel only 250 feet through the new system due to improved material flow and single piece flow, as opposed to 720 feet in the existing system. The new system design with improved material and information flows has helped decrease the throughput time to 42 minutes, an incredible reduction from 46 hours, which includes machining. Quality has been improved in the new DEW98 assembly cell as well. This is largely due to the visibility of the new system design. Quality issues are very difficult to track in the WIN88 asynchronous assembly line. The number of defective parts per day for the new manufacturing system is only 30-40 pieces compared with 7.5% defects, or about 285 defective parts per day for the existing system. Also, the first time through (FTT) of the new system is up to 90% from 85% even though the amount of production time lost due to disruptions has increased slightly from 16 to 24 minutes per hour. Some improvements have been made regarding the operators as well. Non-value-adding work has been decreased from about 35% to about 25%, and non-value-adding movement has been reduced from about 30% to about 25%. The application of the key performance measurements to the Indianapolis Plant shows that the new DEW98 system design for steering gears has far superior performance over the existing WIN88 manufacturing system.

6.3.4 Application of the MSD Evaluation Tool at Indianapolis U222 – After Using the MSD Decomposition

The newly designed U222 manufacturing system for steering gears at Indianapolis is shown in Figure 6.14. This manufacturing system design is also an assembly cell operating at a defined takt time, similar to the DEW98 assembly cell. All operations are balanced to the takt time, and there are no integrated repair loops or parallel processing operations to complicate the material flow. The estimated throughput time for the U222 assembly cell is a very predictable 40 minutes, instead of 46 hours for the WIN88 assembly line. In addition, inventory and work in process (WIP) levels should be reduced and standardized so that they may be visually controlled throughout the system. The U222 assembly cell has not yet been implemented so the numbers presented here are all estimates.

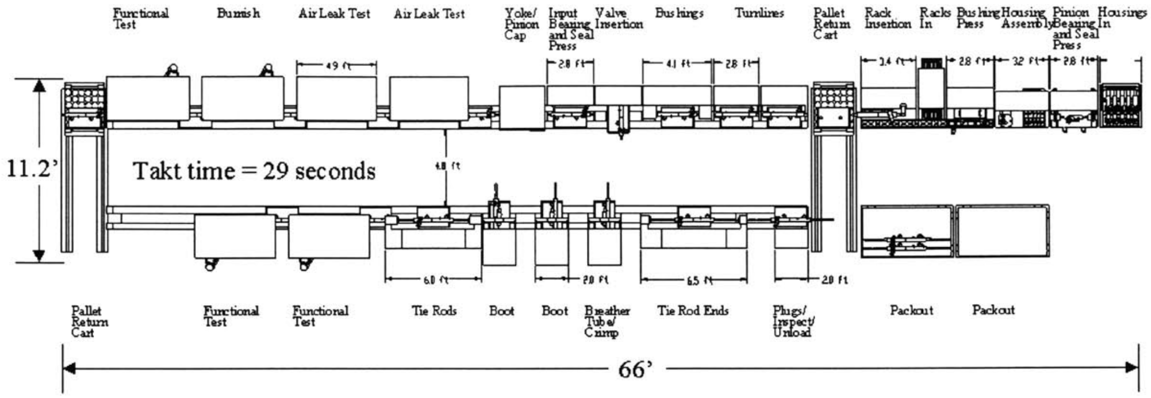


Figure 6.14: New Indianapolis U222 Assembly Cell Layout for Manufacturing Steering Gears

The U222 assembly cell makes similar improvements over the WIN88 asynchronous assembly line as the DEW98 assembly cell discussed previously; however, the improvements will hopefully be more refined and better accomplished in the U222 assembly cell. Operators have defined workloops to operate multiple work stations as well as standard work instructions, which have eliminated both ergonomic issues and non-value-adding tasks and motions in the work stations. The number of operators in the assembly cell can be varied in order to achieve volume flexibility. Quality problems will be largely eliminated, and any remaining problems and their root causes will be more easily tracked and eliminated in this system.

After designing the new U222 manufacturing system for steering gears at the Indianapolis Plant, the MSD Evaluation Tool was again applied to the system, and the evaluation is shown in Figure 6.15. The new manufacturing system design falls mostly in Levels 3 and 4, part of the system is at Level 5, very little of the system rates at Level 2, and none of the system is evaluated at Level 1.

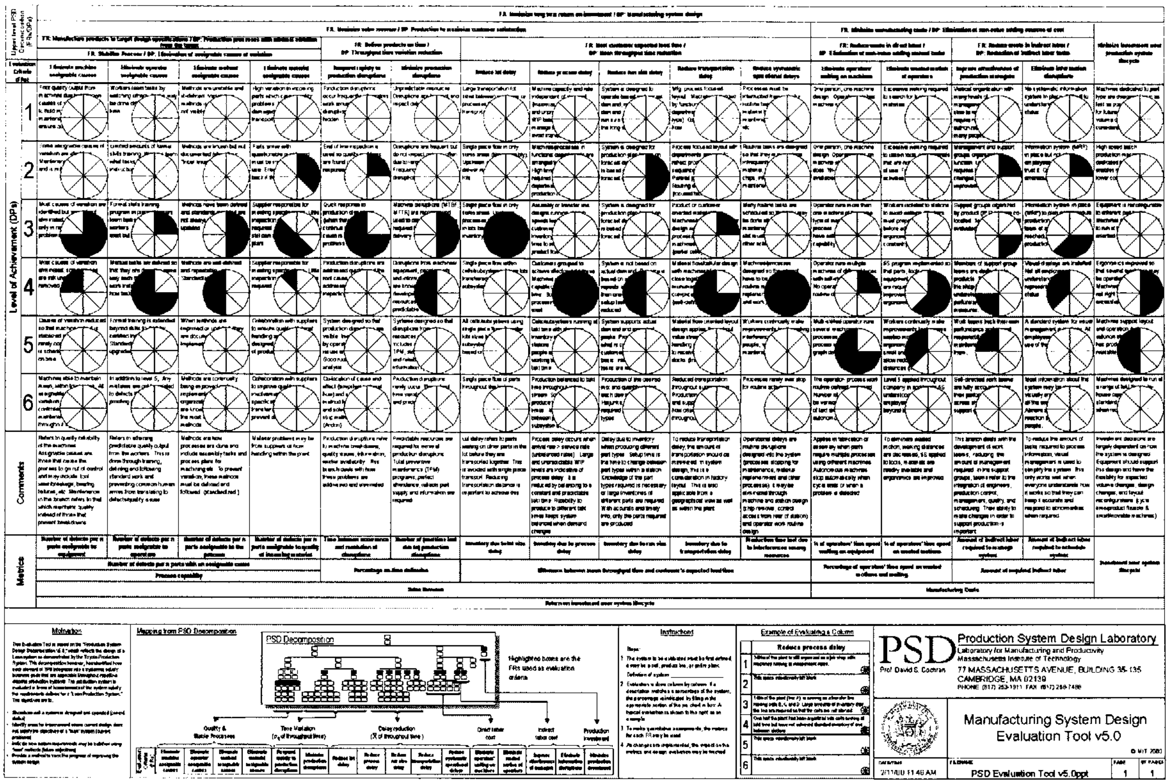


Figure 6.15: MSD Evaluation Tool for the New Indianapolis U222 Assembly Cell for Manufacturing Steering Gears - After

By comparing the applications of the MSD Evaluation Tool to the WIN88 asynchronous assembly line and the U222 assembly cell at Indianapolis, it becomes visually apparent that the entire system design has been improved dramatically, and the two systems can be compared column by column for more specific information about the areas of improvement. For example, 'Respond rapidly to production disruptions,' previously the worst column of the evaluation with 75% at Level 1 and 25% at Level 2, is now 25% at Level 2 and 75% at Level 3. The most significant improvements occurred in 'Eliminate operators' waiting on machines' and 'Minimize investment over production system lifecycle.' 'Eliminate operators' waiting on machines' improved from 50% each at Levels 1 and 2 to a far better 25% at Level 4 and 75% at Level 5. 'Minimize investment over production system lifecycle' improved from 25% at Level 1, 62.5% at Level 2, and 12.5% at Level 3 to a significantly better 50% each at Levels 4 and 5. The new system design evaluation shows that all areas of the manufacturing system design for U222 steering gears at Indianapolis improved over the manufacturing system for WIN88 steering gears. However, the system design can still be improved in all areas, and the MSD Evaluation Tool shows in which areas further improvements can still be made.

6.3.5 Application of Key Performance Measurements at Indianapolis U222

In addition to the MSD Evaluation Tool, key performance measurements were applied to the WIN88 and U222 manufacturing systems for steering gears at the Indianapolis Plant, and they are shown in Figure 6.16.

Performance Measurements Worksheet - Indy U222

	State of the Manufacturing System		Normalized Comparison	
	Before - Mass	After - Lean		
Brief Description of the Manufacturing System	WIN88 Asynchronous Assembly Line	U222 Assembly Cell	**After - Lean**	**Before - Mass**
Production volume per day	3800	990	1.00	3.84
Number of shifts per day	2	2	1.00	1.00
Production pieces per hour	260	124	1.00	2.10
Line cycle time or Takt time	13.8 sec	29 sec	1.00	0.48
Work in process	270	30	1.00	9.00
Inventory (number of parts)	13000 (finished goods)	~5000	1.00	2.60
Floor space consumed	20000 sq. ft.	1500 sq. ft.	1.00	13.33
Total distance parts travel	720 ft.	190 ft.	1.00	3.79
Average number of defects per month	~285 / day	10 / day	1.00	28.50
Number of direct workers	32	12	1.00	2.67
Operator hours required per part	12.3 min	13 min	1.00	0.95
Percent operators' time doing NVA work*	35%	20%	1.00	1.75
Percent operators' time for NVA movement*	30%	20%	1.00	1.50
Overtime required per day	2 hr	0	1.00	N/A
Percent absenteeism per month	12%	12%	1.00	1.00
Number of indirect workers required to manage and schedule the system	1.14	1.14	1.00	1.00
Customer expected lead time	-	-	-	-
Throughput time of system	46 hr	40 min	1.00	69.00
Material replenishment rate	unpredictable	2 hrs	1.00	N/A
FTT (First time through)	85%	98%	1.00	0.87
Production time lost due to disruptions	16 min/hr	9 min/hr	1.00	1.78
Percent on-time deliveries	-	-	-	-
Additional Performance Measurements				
Support personnel (excl. mgmt. & super.)	7	-	-	N/A
Repair personnel	3	-	-	N/A
Number of models	5	2	1.00	2.50
Notes:				
* NVA work refers to non-value adding manual tasks				
* NVA movement refers to non-value adding walking, searching for tools, parts, etc.				

Figure 6.16: Performance Measurements Worksheet for Indianapolis U222

The comparison of the key performance measurements for the existing WIN88 asynchronous assembly line with the new U222 assembly cell is largely similar to the comparison of key performance measurements between the WIN88 assembly line and DEW98 assembly cell discussed previously. Again, this comparison is not based on equivalent volume of production because the WIN88 and U222 systems produce different product models of steering gears. However, the analysis shows that the new system will be capable of meeting customer demand with far less work in process (WIP) and finished goods inventory. Moreover, the assembly cell will operate at a reasonable takt time of 29 seconds whereas the existing assembly line has an extremely short cycle time of only 13.8 seconds. The new assembly cell also will take up much less floorspace, only an estimated 1500 square feet instead of 20,000 square feet. Also, the parts will travel only an estimated 190 feet through the new system due to improved material flow as opposed to 720 feet in the existing system. The new system design with improved material and information flows should decrease the throughput time to an estimated 40 minutes, an astounding reduction from 46 hours. Quality will be improved drastically in the new assembly cell for U222 as well. This again is largely due to the visibility of the new system design. Quality issues are difficult to track in the WIN88 asynchronous assembly line. The number of defective parts per day for the new manufacturing system is estimated to be only 10 pieces compared with about 285 defective parts per day for the existing system. The first time through (FTT) of the new system is estimated to be 98%, which is even higher than the FTT of 90% for the DEW98 system design, and the amount of production time lost due to disruptions should decrease slightly from 16 to 9 minutes per hour. Some improvements have been made regarding the operators as well. Non-value-adding work should decrease from about 35% to about 20%, and non-value-adding movement should be reduced from about 30% to about 20%. The application of the key performance measurements to the Indianapolis Plant shows that the new U222 system design for steering gears will have far superior performance over the existing WIN88 manufacturing system and will also have much better performance than the DEW98 manufacturing system design.

6.4 Monroe Chassis Components and Systems Plant

The Monroe Plant manufactures several different products for automobiles. These products include steel wheels, coil springs, stabilizer bars, catalytic converters, body components, and hot stampings. Annually, Monroe manufactures 38 million components with 2163 employees. The manufacturing facility occupies 1.5 million square feet.

In this project, the existing manufacturing system for catalytic converters uses three individual lines, which have no standard linkage between them. These three lines are to be converted from a "push" system into two independent cells after "lean" implementation [Carrus, 2000 and Mierzejewska, 2000].

6.4.1 Application of the MSD Evaluation Tool at Monroe – Before Using the MSD Decomposition

The existing system for catalytic converters at the Monroe Plant is shown in Figure 6.17. This manufacturing system is scheduled based on forecast demand, not actual demand, using centralized, multiple point instruction to control information flow. Along with the information flow, the material flow is also very complicated. As a result, the throughput times are unpredictable and vary between fifteen minutes and four hours. Large and hidden inventory and work in process (WIP) can be found in many locations throughout this system.

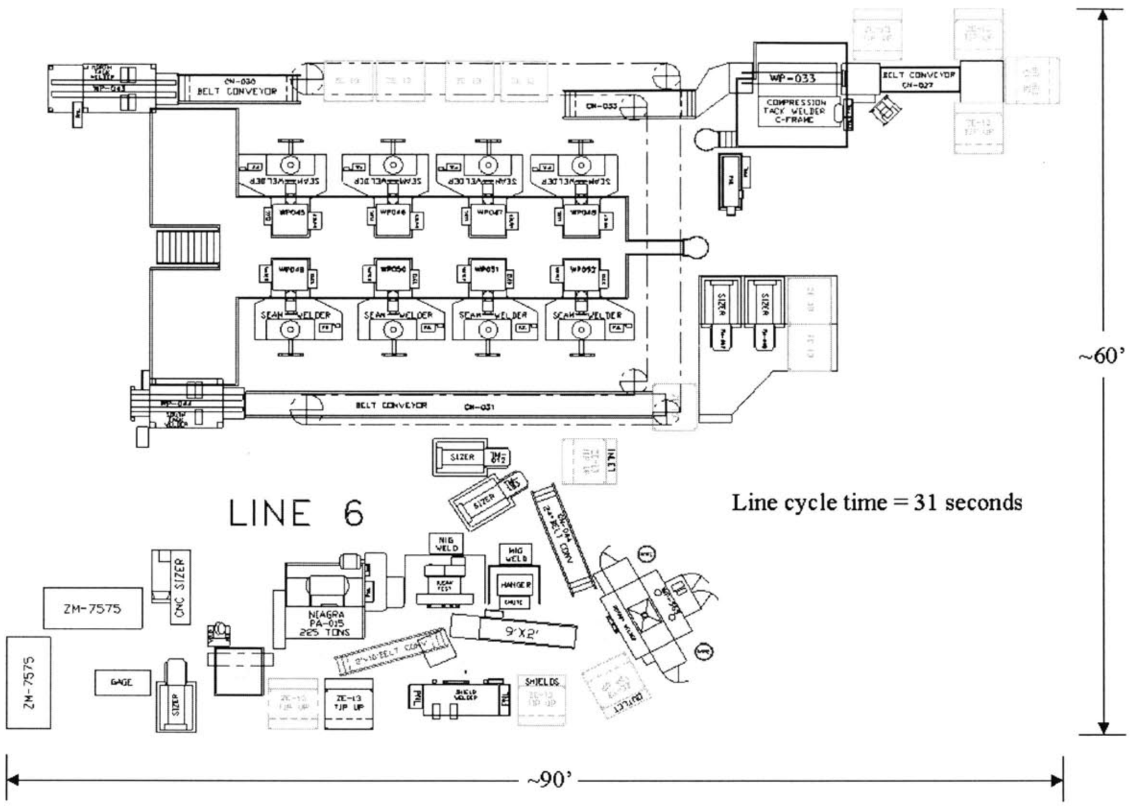


Figure 6.17: Existing Monroe Assembly Line Layout for Manufacturing Catalytic Converters

Operators are tied to individual machines or stations, and changeovers of machines are very disruptive to production. The operators have no defined, standard work instructions, which results in many ergonomic problems and non-value-adding tasks and motions. All of the unpredictabilities in the existing system make it very difficult to identify and eliminate defects and their root causes.

The MSD Evaluation Tool was applied to the existing system at the Monroe Plant, and the evaluation is shown in Figure 6.18. The existing manufacturing system falls between Levels 1-4, mostly in Levels 2 and 3, and no aspects of the system rate above Level 4.

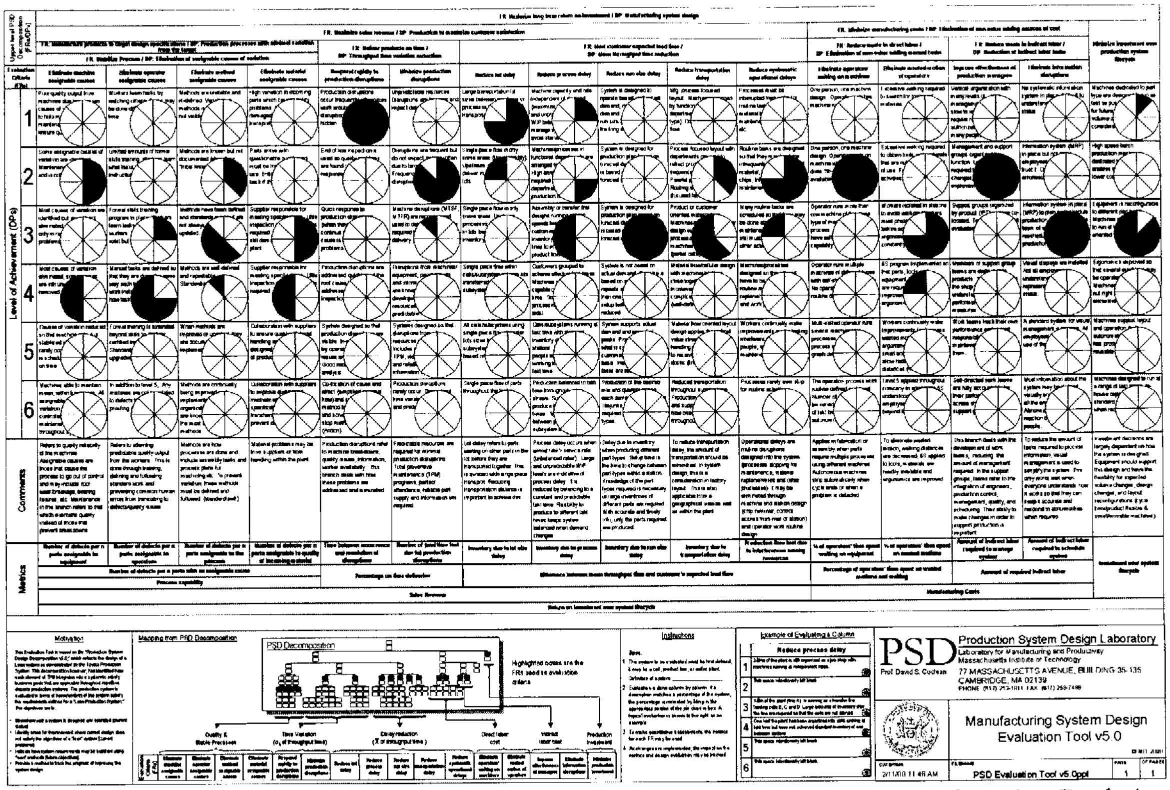


Figure 6.18: MSD Evaluation Tool for the Existing Monroe Assembly Line for Manufacturing Catalytic Converters - Before

Through application of the MSD Evaluation Tool to the existing system at Monroe, it becomes visually apparent that the entire system can be improved overall, and each column of the MSD Evaluation Tool provides more insight into specific needs for improvement. For example, the worst column for Monroe is 'Respond rapidly to production disruptions,' which is evaluated to be entirely at Level 1. Other extremely weak areas of the existing system are 'Reduce lot delay,' 'Eliminate operators' waiting on machines,' 'Improve effectiveness of production managers,' and 'Minimize production disruptions.'

6.4.2 Application of the MSD Evaluation Tool at Monroe – After Using the MSD Decomposition

The newly designed manufacturing system at Monroe is shown in Figure 6.19. This manufacturing system is scheduled according to actual customer consumption, not forecast demand, using single point instruction to control information flow. Along with the information flow, the material flow has also been simplified to a FIFO system (first-in-first-out). As a result, the throughput times have been reduced to a very predictable ten minutes. In addition, inventory and work in process (WIP) levels have been reduced and standardized so that they may be visually controlled throughout the system.

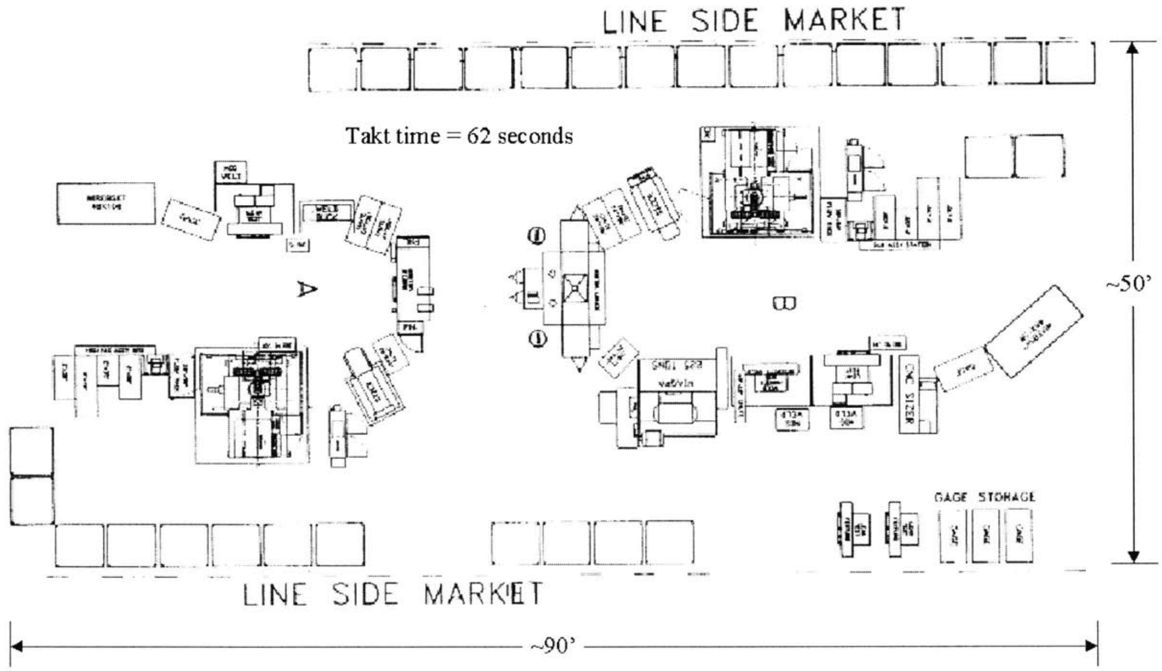


Figure 6.19: New Monroe Two Assembly Cell Layout for Manufacturing Catalytic Converters

Operators now have defined workloops to operate multiple machines and stations, and changeovers of machines are quick and easy. The operators have defined, standard work instructions, which have eliminated both ergonomic issues and non-value-adding tasks and motions through the use of kaizen, or continuous improvement activities [Imai, 1986]. The unpredictabilities in the manufacturing system either have been eliminated or are being eliminated continuously so that it is much easier to identify and eliminate defects and their root causes.

After the existing manufacturing system for catalytic converters at the Monroe Plant was converted to two independent cells, the MSD Evaluation Tool was again applied to the system, and the evaluation is shown in Figure 6.20. The new manufacturing system design falls mostly in Levels 3 and 4, and extremely little of the system rates at Level 1.

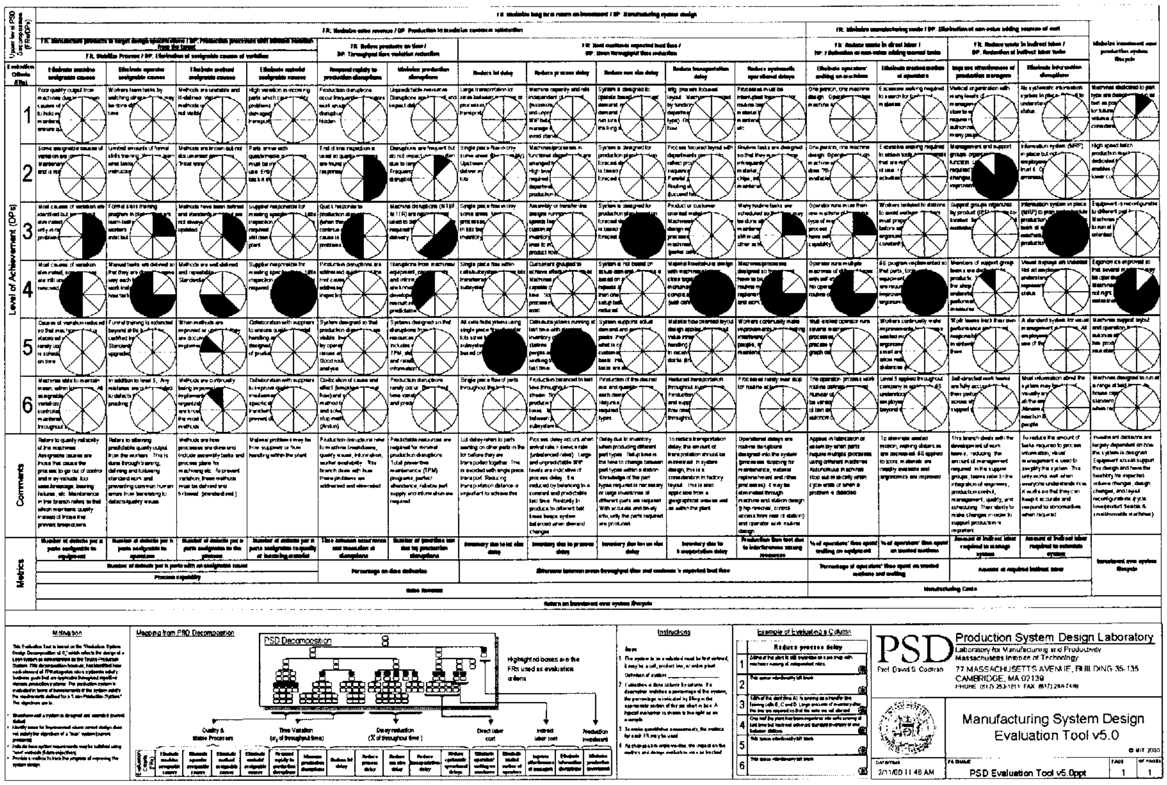


Figure 6.20: MSD Evaluation Tool for the New Monroe Assembly Cells for Manufacturing Catalytic Converters - After

By comparing the applications of the MSD Evaluation Tool to the existing system and new system design at Monroe, it becomes visually apparent that the entire system design has been improved dramatically, and the two systems can be compared column by column for more specific information about the areas of improvement. For example, 'Respond rapidly to production disruptions,' previously the worst column of the evaluation entirely at Level 1, is now 50% at Level 2 and 50% at Level 3. The most incredible improvement occurred in 'Reduce lot delay,' which improved from 75% at Level 1 and 25% at Level 2 to an astonishing 100% at Level 5. The new system design evaluation shows that nearly all areas of the manufacturing system at Monroe improved, only 3 areas remained the same as the existing system, and no areas of the new manufacturing system design were rated poorer than the existing system. However, having some areas of the evaluation at Level 5 or 6 and other areas at Level 1 or 2 does not indicate a coherent system design. The manufacturing system design can still be improved in all areas, and the MSD Evaluation Tool shows in which areas further improvements can still be made.

6.4.3 Application of Key Performance Measurements at Monroe

In addition to the MSD Evaluation Tool, key performance measurements were applied to the catalytic converter manufacturing systems at the Monroe Plant, and they are shown in Figure 6.21.

Performance Measurements Worksheet - Monroe					
	State of the Manufacturing System			Normalized Comparison	
	Before - Mass	After - Lean			
Brief Description of the Manufacturing System	3 Lines, Push system, No standard linkage	2 Independent cells		After - Lean	Before - Mass
		Cell 1	Cell 2		
Production volume per day	1600	1200	400	1.00	1.00
Number of shifts per day	2	3	1	1.00	1.00
Production pieces per hour	116		58	1.00	2.00
Line cycle time or Takt time	31 sec		62 sec	1.00	0.50
Work in process	1000		15	1.00	66.67
Inventory (number of parts)	large and variable		3 days	1.00	N/A
Floor space consumed	5000 sq. ft.		4600 sq. ft.	1.00	1.09
Total distance parts travel	329 ft.		68 ft.	1.00	4.84
Average number of defects per month	300 pcs		100 pcs	1.00	3.00
Number of direct workers	14	8	3	1.00	1.27
Operator hours required per part	6.24 worker-min/part	6.02 worker-min/part		1.00	1.04
Percent operators' time doing NVA work*	30%		10%	1.00	3.00
Percent operators' time for NVA movement*	10%		9%	1.00	1.11
Overtime required per day	1 hr		1 hr	1.00	1.00
Percent absenteeism per month	5%		5%	1.00	1.00
Number of indirect workers required to manage and schedule the system	6		4	1.00	1.50
Customer expected lead time	3 days		3 days	1.00	1.00
Throughput time of system	182 hrs		92 hrs	1.00	1.98
Material replenishment rate	2 hrs		20 min	1.00	6.00
FTT (First time through)	26%		52%	1.00	0.50
Production time lost due to disruptions	38 min		78 min	1.00	0.49
Percent on-time deliveries	95%		99%	1.00	0.96
Notes:					
* NVA work refers to non-value adding manual tasks					
* NVA movement refers to non-value adding walking, searching for tools, parts, etc.					

Figure 6.21: Performance Measurements Worksheet for Monroe

The comparison of the key performance measurements for the existing system of three lines with the new system design of two independent cells shows that the new system is capable of producing the same volume of parts with far less inventory and work in process (WIP). Moreover, the assembly cells operate at a takt time of 62 seconds whereas the existing assembly line has a cycle time of only 31 seconds. Also, the parts travel only 68 feet through the new system due to improved material flow as opposed to 329 feet in the existing system. The new system design with improved material and information flows has helped decrease the throughput time to 92 hours, half of the existing system's 182 hours, and materials are replenished every 20 minutes in the new system instead of every 2 hours. Interestingly, even though the amount of production time lost due to disruptions has increased from 38 minutes to 78 minutes, the percent of on-time deliveries has increased from 95% to 99%. This is largely due to the improvements in quality. The new system has improved quality to 52% over 26% FTT in the existing system, and the number of defective parts per month has been decreased from 300 to 100 pieces. Some improvements have been made regarding the operators as well. Non-value-adding work has decreased from about 30% to about 10%, and non-value-adding movement has been slightly reduced from about 10% to 9%. The application of the key performance measurements to the Monroe Plant shows that the new system design has far superior performance over the existing system.

6.5 Sterling Heights Axle and Driveline Systems Plant

The Sterling Heights Axle Plant manufactures several different products for automobiles. These products include front axles, rear axles, and driveshafts. Weekly, Sterling manufactures 70,000 axles with 4000 employees. The manufacturing facility occupies 2.7 million square feet.

In this project, the existing manufacturing system to produce gears is compared with a new integrated, cellular manufacturing system designed to produce a new product line. Much of the evaluation information are projections based on the new system design because the new manufacturing system will not be operating until about a year from now [Duda, Cochran, Castaneda-Vega, 1999].

6.5.1 Application of the MSD Evaluation Tool at Sterling – Before Using the MSD Decomposition

The existing system at the Sterling Heights Axle Plant for gear manufacturing is shown in Figure 6.22. This figure shows only the machining areas for the gears, but it is clear that the material and information flows in this system are extremely complicated. As a result, the Dock-to-Dock time can be as long as 20 days. Large amounts of inventory and work in process (WIP) abound throughout this complex manufacturing system.

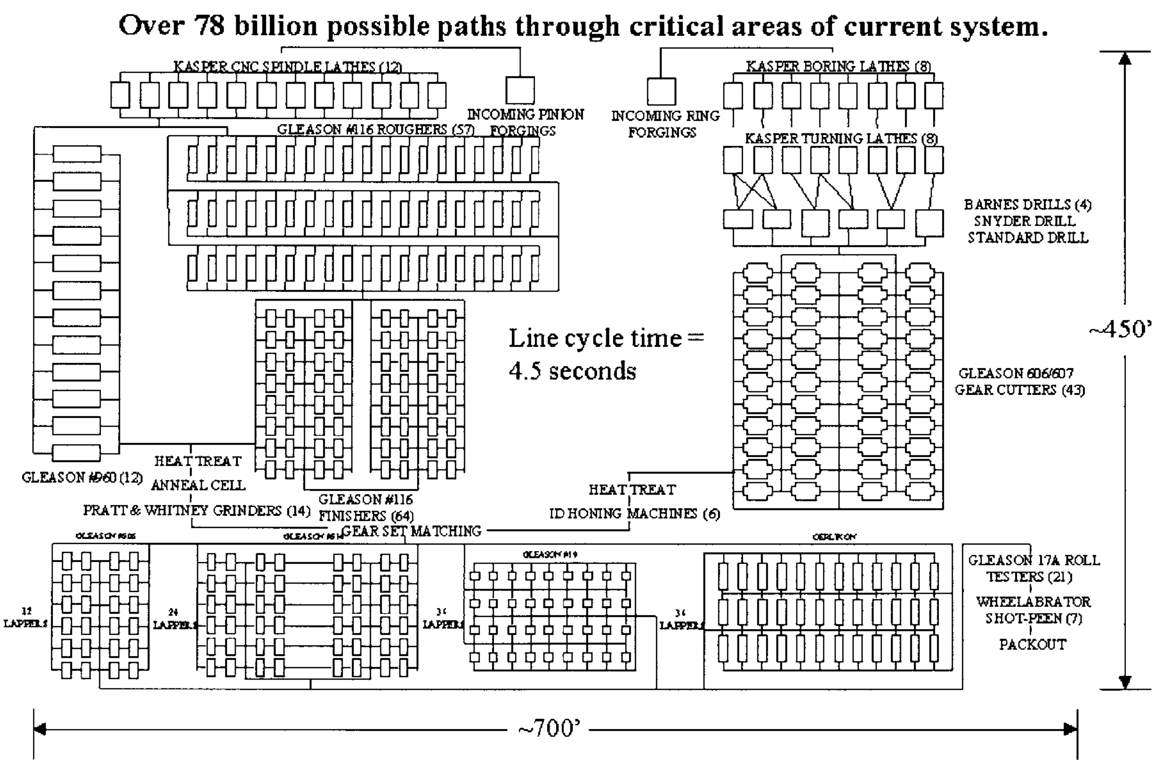


Figure 6.22: Existing Sterling Manufacturing System Layout for Manufacturing Gears

The current system is designed for mass production in a process flow layout. There is much parallel processing as parts travel from department to department due to mismatched cycle times of the equipment. In addition, the equipment is not very reliable, and changeovers consume an inordinate amount of time. Furthermore, the quality problems are very difficult to eliminate because the material flow is nearly impossible to trace in this complicated system.

The MSD Evaluation Tool was applied to the existing system at the Sterling Heights Axle Plant, and the evaluation is shown in Figure 6.23. The existing manufacturing system falls between Levels 1-5, mostly in Levels 2-4, and very few aspects of the system rate at or above Level 5.

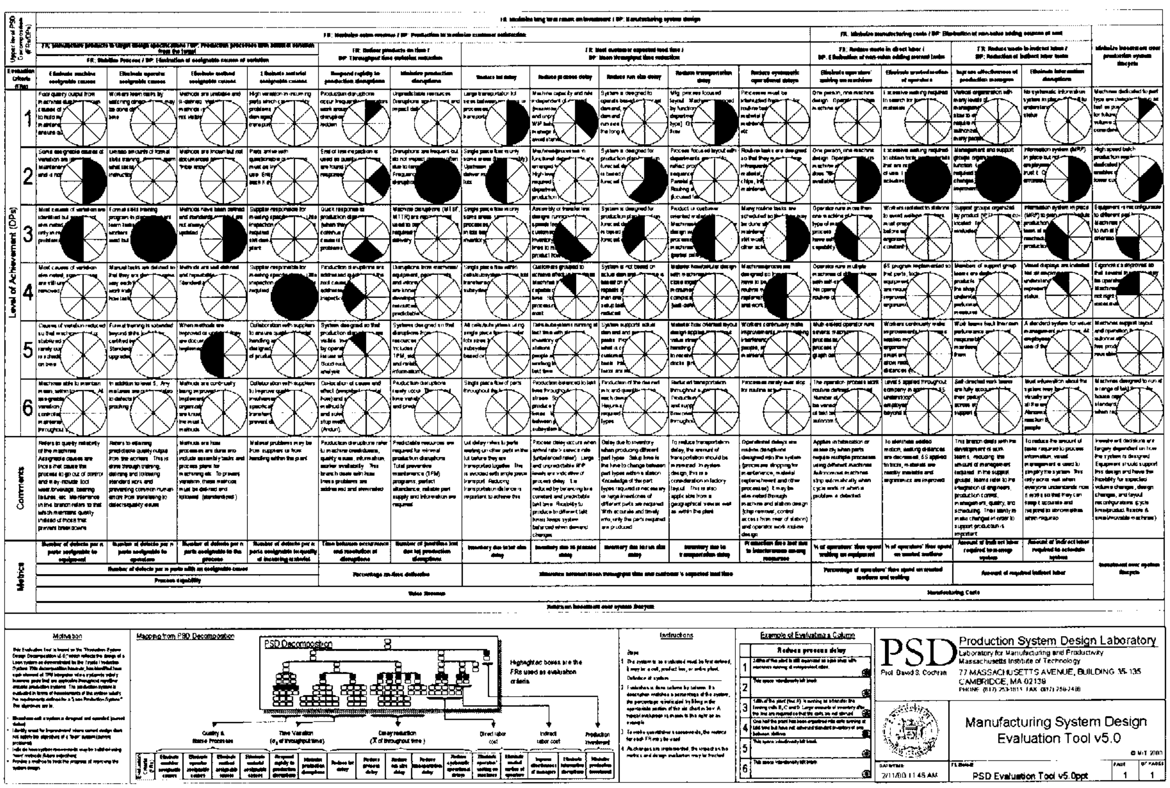


Figure 6.23: MSD Evaluation Tool for the Existing Sterling Manufacturing System for Manufacturing Axles - Before

Through application of the MSD Evaluation Tool to the existing system at Sterling, it becomes visually apparent that the entire system can be improved overall, and each column of the MSD Evaluation Tool provides more insight into specific needs for improvement. For example, the worst columns for Sterling are 'Minimize production disruptions,' 'Reduce lot delay,' 'Eliminate wasted motion of operators,' and 'Improve effectiveness of production managers,' which are all evaluated to be at Level 2 or below.

6.5.2 Application of the MSD Evaluation Tool at Sterling – After Using the MSD Decomposition

The newly designed manufacturing system at Sterling is shown in Figure 6.24. The 'Finish Machining' and 'Dry Face Hob' cells in this figure perform all the operations of the gear machining areas shown in Figure 6.22 of the existing manufacturing system. This integrated cellular system design has extremely simplified material and information flows compared with the existing mass production system. As a result, the Dock-to-Dock time has been reduced to only 2 days. In addition, inventory and work in process (WIP) levels have been reduced and standardized so that they may be visually controlled throughout the system.

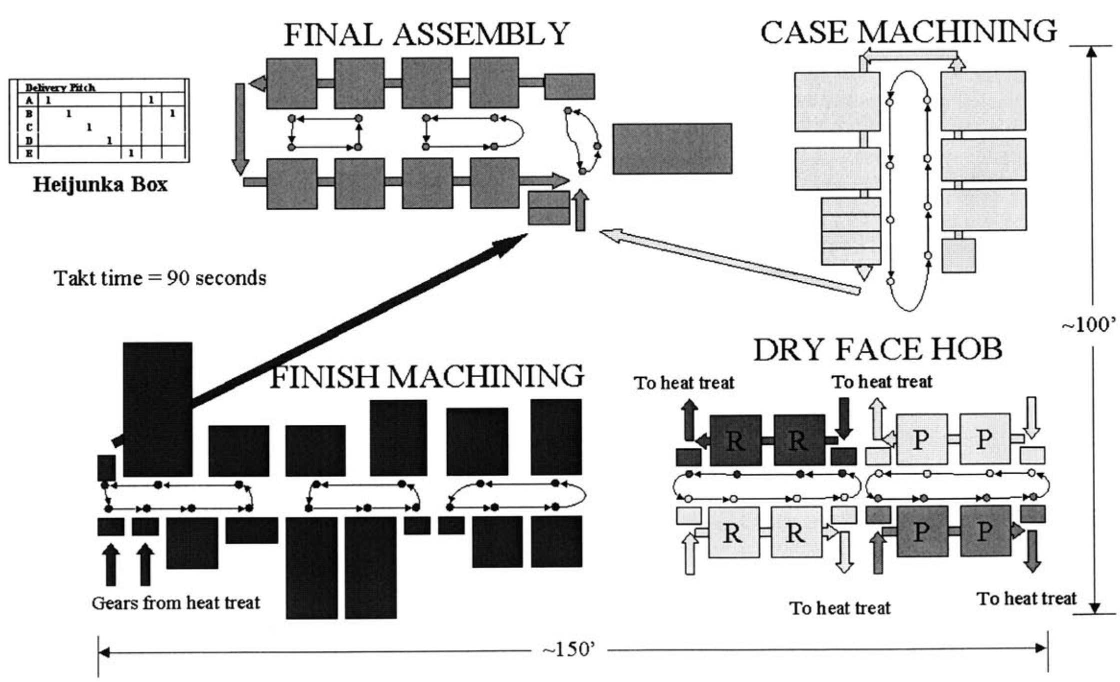


Figure 6.24: New Sterling Manufacturing System Layout for Manufacturing a New Product Line

The equipment and machines are all right sized and designed for use in the new system. They operate with matched cycle times which are able to meet the defined takt time for the system, and parallel processing has been eliminated. The operators now have defined workloops to operate multiple machines and stations, and changeovers of some machines are quick and easy. The unpredictabilities in the manufacturing system either have been eliminated or are being eliminated continuously so that it is much easier to identify and eliminate defects and their root causes.

After the new integrated cellular system was designed for the Sterling Heights Axle Plant, the MSD Evaluation Tool was again applied to the system, and the evaluation is shown in Figure 6.25. The new manufacturing system design falls mostly in Levels 5 and 6, very little of the system rates below Level 5, and none of the system is evaluated at Levels 1 and 2.

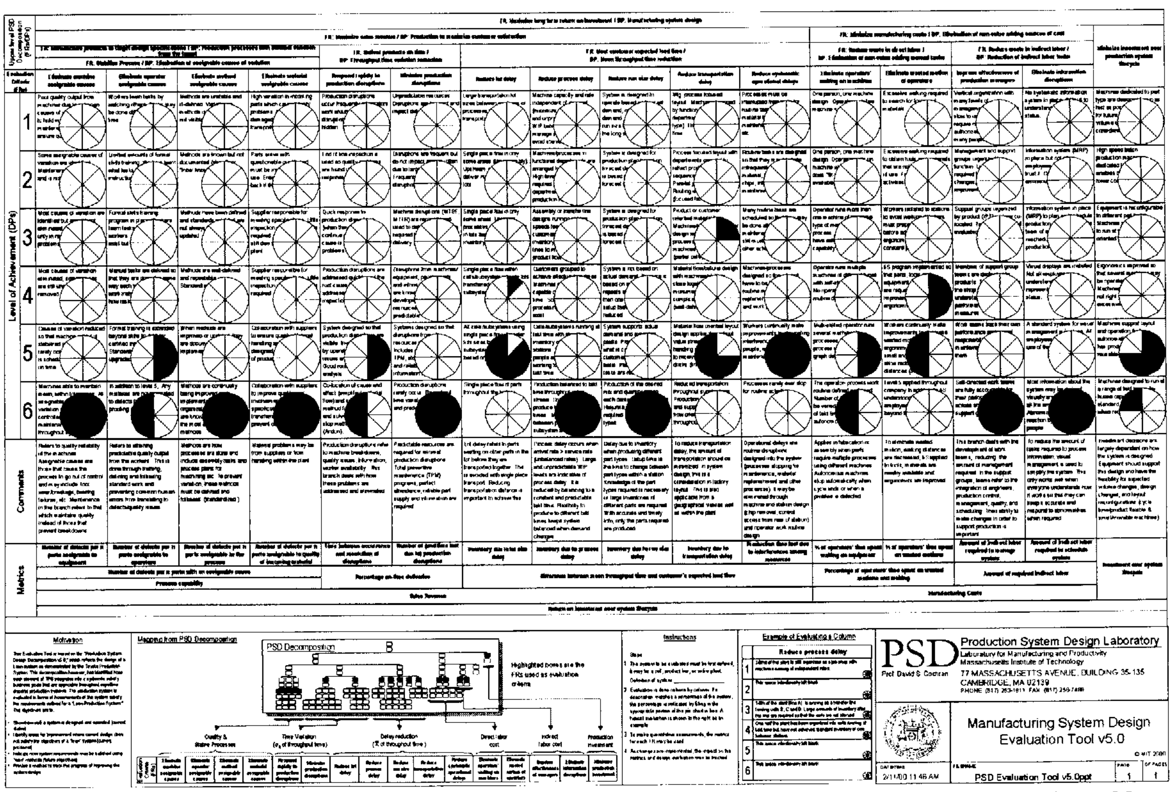


Figure 6.25: MSD Evaluation Tool for the New Sterling Manufacturing System for Manufacturing a New Product Line - After

By comparing the applications of the MSD Evaluation Tool to the existing system and new system design at Sterling, it becomes visually apparent that the entire system design has been improved dramatically, and the two systems can be compared column by column for more specific information about the areas of improvement. For example, 'Minimize production disruptions' and 'Improve effectiveness of production managers,' previously two of the worst columns of the evaluation entirely at Level 2, have now been upgraded to entirely at Level 6. These two areas showed the most significant improvement over the existing system. Furthermore, most of the new system is evaluated at Levels 5 and 6, showing great system-wide enhancement over the existing manufacturing system which is evaluated mostly between Levels 2-4. The new system design evaluation shows that all areas of the manufacturing system at Sterling improved over the existing system. However, the system design can still be improved in many areas, and the MSD Evaluation Tool shows in which areas further improvements can still be made. Even though a manufacturing system design may be evaluated at Level 6, there will still be continuous improvements which can further improve the system's effectiveness.

6.5.3 Application of Key Performance Measurements at Sterling

In addition to the MSD Evaluation Tool, key performance measurements were applied to the Sterling Heights Axle Plant, and they are shown in Figure 6.26.

Performance Measurements Worksheet - Sterling				
	State of the Manufacturing System		Normalized Comparison	
	Before - Mass	After - Lean		
Brief Description of the Manufacturing System	Existing system to produce old products	Production system design for a new product	After - Lean	Before - Mass
Production volume per day	~10000	~500	1.00	20.00
Number of shifts per day	1-3, depending on area	1 to 3	1.00	1.00
Production pieces per hour	~800	~40	1.00	20.00
Line cycle time or Takt time	4.5 sec	90 sec	1.00	0.05
Work in process	4-14 days	~2 days, + outsourcing	1.00	4.50
Inventory (number of parts)	~100,000	~1000	1.00	100.00
Floor space consumed	~1.5 million sq. ft.	14500 sq. ft.	1.00	103.45
Total distance parts travel	~1.5 miles	1500 ft., + outsourcing	1.00	5.28
Average number of defects per month	10000	1500	1.00	6.67
Number of direct workers	2000 / shift	12 / shift	1.00	166.67
Operator hours required per part	3	2.6	1.00	1.15
Percent operators' time doing NVA work*	5 - 50%	30 - 80%	1.00	0.41
Percent operators' time for NVA movement*	5 - 50%	10 - 30%	1.00	1.13
Overtime required per day	1 hr	0 hr	1.00	N/A
Percent absenteeism per month	4	0	1.00	N/A
Number of indirect workers required to manage and schedule the system	50	1 supervisor	1.00	50.00
Customer expected lead time	2 wks	2 wks	1.00	1.00
Throughput time of system	~8 days	~2 days, + outsourcing	1.00	4.00
Material replenishment rate	6 sec to 8 hrs	1 min to 4 hrs	1.00	N/A
FTT (First time through)	70%	90%	1.00	0.78
Production time lost due to disruptions	1 day/wk	1 day/month	1.00	4.00
Percent on-time deliveries	99.99%	99.99%	1.00	1.00

Notes:
* NVA work refers to non-value adding manual tasks
* NVA movement refers to non-value adding walking, searching for tools, parts, etc.
** The new production system will not be running for about another year

Figure 6.26: Performance Measurements Worksheet for Sterling

The comparison of the key performance measurements for the existing system with the new integrated cellular system design is not based on equivalent volume of production because the new system design will produce a different product model from the existing system. However, the comparison shows that the new system design is capable of meeting customer demand with far less inventory and work in process (WIP). Moreover, the new system design will operate at a reasonable takt time of 90 seconds whereas the existing system has an extremely short cycle time of only 4.5 seconds. The new system design will consume only an estimated 14,500 square feet of floorspace compared to about 1.5 million square feet for the existing system. Also, the parts will travel only an estimated 1500 feet within the plant for the new system as opposed to approximately 1.5 miles in the existing, complicated, departmental system. The new system design with improved material and information flows should decrease the throughput time to just about 2 days from approximately 8 days for the existing system, and materials will be replenished more frequently and predictably. The new system should also improve quality and reduce the amount of time lost due to disruptions from approximately 1 day per week to only an estimated 1 day per month. In addition, the new system design should improve first time through (FTT) to 90% over the existing 70%, and the number of defective parts per month should drop from about 100,000 to only an estimated 1000. The application of the key performance measurements to the Sterling Heights Axle Plant shows that the new system design will have far superior performance over the existing system when it is implemented.

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