AN EVALUATION OF THE DESIGN OF MANUFACTURING MEASURABLES FOR THE FORD PRODUCTION SYSTEM

by

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Submitted to the Sloan School of Management
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ABSTRACT

This research performs a design evaluation of the performance measures developed by Ford Motor Company to support its manufacturing operations. To become more competitive in the automotive industry, Ford is reengineering its core business processes, including the Ford Production System (FPS). The "lean" production methods used by the Toyota Production System serve as a benchmark for the changes being made to Ford's manufacturing system. A set of performance metrics has been developed to monitor improvement and align the objectives of management.

The process used by Ford to design the FPS measures is examined. Interview data and a survey of plant management are used to determine the objectives and current use of manufacturing measures. The axiomatic design methodology provides a framework for evaluating the FPS design. Functional Requirements and Design Parameters for the design of a lean production system are developed and compared to the Ford case. A control hierarchy is described, in which measures are designed to support management decision-making at different levels in the organization. The measures are evaluated as to how well they support the steps required in forming a lean production organization.

Results from the design analysis indicate that the Ford measurables do not support all of the company's objectives. Recommendations include the use of a structured design approach to develop appropriate measures for each level of a control hierarchy. This control hierarchy defines the information flow and decision control points. Specific measures to support lean production practices are outlined. The design methodology described is useful for any firm wishing to develop metrics to match their business goals.

Thesis Supervisors:
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I greatly acknowledge the Leaders for Manufacturing Program for its support of this work. I would also like to thank my thesis advisors, Professor Charlie Fine and Professor David Cochran, for their help and advice. The use of the axiomatic design methodology is based on Professor Cochran's work in the design of manufacturing systems.

I would like to thank my friends and fellow classmates, especially Dave Myron, Mark MacLean, Eric Hooper, and my good friend Mark Newcombe for the help they provided throughout the production of this thesis.

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1. Overview

1.1 Introduction

Since the early 1980’s, American manufacturing firms have been under close scrutiny. The traditional mass production system used by these firms, widespread since the early days of the automotive industry, finds itself in competition with a new set of ideas pioneered by Japanese companies such as Toyota, and grouped under the term "lean production" [36]. This new method of manufacturing has been so successful against the world’s industrial giants, that many U.S. firms are reengineering their operations to take advantage of these powerful ideas. Now, Ford Motor Company, whose founder’s name is almost synonymous with mass production, is becoming one of the largest companies to undertake this transition.

The differences between mass production and lean production are dramatic. Traditional production systems are designed to manufacture standardized products at very high volumes, using expensive, single-purpose equipment and a low-skilled workforce. Lean production seeks instead to be able to produce a high variety of products using flexible equipment and multi-skilled teams. The focus is on zero defects, zero inventory, and on reducing costs. Toyota is perhaps the best known and documented of the lean producers, and provides Ford with an impressive benchmark for its own production system.

Ford does not want plant-level improvements only, but a corporate-wide implementation of these modern manufacturing techniques. An important part of this implementation is changing the mindset of people and gaining their acceptance. Since it is human nature to behave in the way in which one is measured, the choice of performance measurements is critical in determining whether the transition to the new system of production will be successful. Just as measures such as machine efficiency and direct labor hours were important for the mass production system, certain measures will be important for running a lean production system. This thesis examines the process Ford is using to change their manufacturing measures and to accomplish the transition from traditional mass production to modern lean production methods.
1.2 General Background

In January, 1995, Ford Motor Company officially began Ford 2000, an effort to reengineer the key processes it uses to run its business. To become more competitive in the automotive industry, Ford is implementing radical changes in four core business processes: the Ford Product Development System, Order to Delivery, After Sales Service, and the Ford Production System.

The Ford Production System (FPS) is an initiative to create a set of standard business processes for all of Ford's global manufacturing sites, aligned to one common goal: to "produce exactly what the customer wants, when it's in demand." Ford's vision is to develop a "lean" production system, focused on eliminating waste, empowering its workers, and remaining flexible to meet changes in customer demands. The goal is a common system at manufacturing operations in all regions of the world; not a centralization of management, but decentralized control of the business using a standard set of tools.

The first visible effort of Ford 2000 in the manufacturing arena is the launch of a common set of manufacturing measurables. The FPS measurables are a set of plant data used to evaluate performance of the plant in meeting the goals of FPS. The plan is for the FPS measurables to drive continuous improvement and support the Plant Operating System - the set of processes being developed over the next several years to revise the current production system in order to meet the vision of lean production. The new measurables were launched at all manufacturing sites at the beginning of 1996, and will be used in plant management's performance evaluation and reward structure.

1.3 Goals and Objectives

The goal of this thesis is to examine the design problem of choosing performance metrics to use for the Ford Production System. It includes the following:

1. A description of the problem of selecting manufacturing measurables which will support lean production.
2. An examination of where Ford's manufacturing system is today and the approach they are taking to change this system.
3. An evaluation of Ford's approach, including an analysis of how well the measurables meet the design goals, what effect Ford can expect the measures to have on management behavior, and recommendations for improvement.

The design analysis will investigate where the new measures will give more or less useful information than current measurement systems, and where there are potential conflicts between the feedback information and the desired results.

Although the discussion and analysis pertain specifically to Ford Motor Company, the ideas presented in the thesis can apply to others who are implementing lean production, or to any firm wishing to develop metrics which match their business goals.

1.4 Methodology

We use data from interviews of FPS management and measurables users at the plant management level, along with Ford's internal documentation, as the primary sources of information. A survey on the use of measurables was also distributed to users at Ford manufacturing sites in North America and Europe. The paper also includes a review of literature on lean production system design and performance measurement, which provides a background for the design problem that Ford is facing.

This study uses three main frameworks for the evaluation of Ford's design:

- Axiomatic design - a design method similar to Quality Functional Deployment, in which the design goals or "customer wants" are translated into functional requirements. In using this methodology, a design is developed to meet these requirements, based on certain axioms or postulates.
- Functions of performance measurables - examining the managerial issues of using the designed measures to "run the business," and how well they meet a set of necessary management functions.
- Comparison to the implementation process of lean production - how do the chosen measures match the key steps required in forming a lean production organization.
1.5 Executive Summary

This research centers on a design analysis of the set of four main manufacturing measures that Ford intends to use at both plant floor and management levels to support the firm's manufacturing operations. A goal of Ford's reengineering effort is to implement practices which will create a lean production system. This study examines specifically how well the measures chosen for the Ford Production System support these lean practices, and recommends a method for designing measures to accomplish this goal. The paper also discusses the role the measures will play in aligning the objectives of management. The development of an effective set of performance measures at the firm in the past has been a subject of great controversy, and this research is an attempt to clarify the issues of this design problem.

This thesis uses three frameworks to evaluate the design of the FPS measurables. In one approach, the axiomatic design methodology is used to develop a list of measures which can support lean production practices, using Toyota's concept of eliminating the seven wastes as a basis for the model. A design for the Toyota system is described, with measures developed to support each level of decision-making in the system: the manufacturing process level, analysis level, and production system design level. This case is compared to Ford's design, in which the measures do not fully support all of the company's objectives for FPS. Additional measures are required to support decisions about plant capacity, process launch times, and the effectiveness of plant workteams. The design study also examines the information coupling created by the use of composite measures such as Overall Equipment Effectiveness, which makes it difficult to control the manufacturing process.

As part of this research, a measurables survey was distributed to plant management to determine how current measures are used. Through the survey results and interviews of Ford management, the study investigates whether the FPS measures meet the needs of management. The Dock-to-Dock time and Build to Schedule measures both provide useful information for supporting the lean practices Ford wishes to implement. The First Time Through quality measure appears to focus on in-process quality only, and does not adequately relate this to the customer. This measure is not well-designed to match the objective of zero-defects, which requires a defect prevention rather than an inspection mindset.
Another approach compares the FPS measures to the steps required to successfully implement lean production. This evaluation looks at other information which will be needed to measure progress in achieving these steps, including such elements as machine layouts, set-up times, and overall measures of productivity. The results indicate that detailed objectives of such FPS programs as level production and synchronous material flow need to be outlined before the proper measures can be designed to support these initiatives. This agrees with the results using the axiomatic design framework in Chapter 4, which recommends that Ford completes the definition of objectives in the form of functional requirements before measurables can be developed.

From the analysis results, this study recommends changes to the measurables design process. Ford needs to clearly define the corporate functions it wants to measure, and then design metrics which monitor these different functions independently. The company has chosen these measures to be "few in number" and common to all plants and levels of management, but these design characteristics will not yield measures which can support Ford's goal of lean production. Ford needs to create better ties between what it is measuring and the detailed initiatives that they are trying to implement. It will be difficult to create a successful production system unless this is accomplished.

1.6 Overview

The chapters of this thesis are organized as follows:

Chapter 2: Provides background material on Ford's reengineering efforts, and a thorough description of the company's model for the new production system. Benchmarks and current practices of lean production techniques at Ford are also discussed. A literature review of lean production and the measurement of manufacturing performance is included.

Chapter 3: Contains a description of the design problem. Included is a detailed plan of the implementation and use of the FPS manufacturing measurables. There is also a discussion of the changes required to Ford's current production system and barriers to the implementation of FPS.
Chapter 4: An evaluation of the measurables design using the axiomatic design framework. The application of this methodology in this context is discussed, and an analysis is performed.

Chapter 5: Describes the measurables survey tool and results. The use of the measurables in meeting a set of management functions is examined, and the strengths and weaknesses of the FPS design are discussed and rated.

Chapter 6: Addresses how the measures fit to the set of steps required to implement lean production. Also discussed is how the FPS measures tie into other areas of Ford 2000.

Chapter 7: Provides a summary and conclusion of this research and recommendations for the future. The success of the design methodology is also discussed.

2. Background

2.1 Ford 2000

2.1.1 Reengineering Effort and Objectives

Ford is currently in the process of reorganizing itself as a company in order to pursue its goal of becoming the world’s leading automaker. This task includes the reengineering of four core business processes: the Ford Product Development System, Order to Delivery, Ford Production System (FPS), and After Sales Service.

This reengineering effort affects all of Ford’s 250,000-plus employees worldwide. The driving force behind these changes is Ford’s recognition that it needs to realign its workforce and improve its operations to compete in the changing global marketplace. Ford’s international product development and manufacturing operations have evolved over more than 80 years and are not standard throughout the company. The competitive environment has changed significantly in the last 10-20 years, with such trends as increased competition from Japanese manufacturers in the U.S. and elsewhere, Japanese transplant automotive production in the U.S.,
and the opportunity for increased sales in developing markets, in Asia and Latin America, for example.

Ford's objectives are to change its operating practices to meet these challenges. The goal is to reduce costs, especially high product development costs, leverage the firm's international operations, and produce cars more efficiently, improving the firm's response to customers' demands. This section will describe Ford's long-term objectives and illustrate the difference between where they currently are and where they hope to be in the future.

2.1.2 Enterprise Model

Ford has developed an overall model for its automotive enterprise. The illustration in Figure 2-1 illustrates how the company's business can be broken-down into its major components. The main core consists of the Ford Product Development System, Order to Delivery, After Sales Service, and the Ford Production System, along with Management Systems which supports these functions. Outside of this core are the three groups of dealers, customers, and suppliers which interact with the core processes.
Much of the business process reengineering work that is being done is in developing these core items separately, although the reengineering management team recognizes that the interfaces between these processes or subsystems is also important.

The model depicts the entire value-chain from suppliers to services provided after the product is sold. It encompasses not just manufacturing but all functions of the company. Note that the Ford Production System has direct interfaces to all other processes except the dealer and customer, and is thus a crucial part of the firm’s operations.
2.2 Ford Production System Overview

2.2.1 Overview of FPS

**FPS Vision**

A *lean, flexible, and disciplined* common production system defined by a set of principles and processes that employs *groups of capable and empowered people* learning and *working safely together* in the production and delivery of products that consistently *exceed customers' expectations* in quality, cost, and time.

*Figure 2-2 Ford Production System Vision Statement*

The design of Ford's production system began with the development of the vision statement shown in Figure 2-2. The key elements of the vision include the following concepts:

1. *Lean* - By Ford's definition, this term refers to process layouts, factory design, and material strategies that move material rapidly and efficiently to and through the plants. This idea implies a just-in-time material replenishment strategy for material movement from suppliers, between operations, and to the customer. The term "lean" was originally coined by an MIT study to describe the manufacturing system design used by Toyota, and it incorporates more than simply a material strategy. The details of lean production are described in Section 2.3.

2. *Flexible* - This term refers to having the ability to change over processes and products within product cycle as well as from current to new model faster in order to meet customer expectations.

3. The idea of having common processes and practices is that Ford wants one system of production procedures across all of the manufacturing organization, with all components of the system in alignment.

4. Ford wants groups of capable, empowered employees who are educated and trained to operate processes and execute the methods and procedures in their plants, participating and influencing improvements.

The development of this vision of FPS was done by a steering committee, assembled from managers representing almost all of the functions which either manufacture product or interface with the manufacturing operations.
The FPS vision represents a fundamental change in philosophy. The objective is to change the current paradigm of "produce the number of scheduled units each day at the lowest variable cost with the highest quality" to produce exactly what the customer wants, exactly when it is in demand [7].

2.2.2 Transition from Traditional Manufacturing System

Early in the FPS planning process, Ford performed a current state analysis in order to indicate where the company is now compared to where they would like it to be. This study includes a description of where Ford thinks its production activities rate on key aspects of lean production. As an internal benchmark for lean production, Ford used the Powertrain Production System (PPS), a set of practices in place at several plants in Ford's Powertrain Operations which were developed based on operations at Toyota. A cross-functional team visited 15 plants in 5 countries and looked at the gap between current manufacturing operations and PPS, including the identification of best practices, barriers to implementation, the reason for the gap, and short-term opportunities for improvement. Table 2-1 indicates Ford's general findings.

<table>
<thead>
<tr>
<th>Traditional Manufacturing</th>
<th>Ford Production System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality, Cost, Quantity</td>
<td>Quality, Cost, Customer Demand, Time</td>
</tr>
</tbody>
</table>

Current State Findings indicate a $900/unit disadvantage to Toyota, $400 in manufacturing activities. (1995 Harbour Report)

<table>
<thead>
<tr>
<th>Major Reasons for Gap:</th>
<th>Potential Improvements:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excessive Inventories</td>
<td>Improved Machine Reliability = $150-200/unit</td>
</tr>
<tr>
<td>Excessive Machine Downtime</td>
<td>In-Station Process Control (ISPC)</td>
</tr>
<tr>
<td>Poor Quality</td>
<td>Level Production</td>
</tr>
<tr>
<td>Schedule Variability</td>
<td>Just-in-Time (JIT)</td>
</tr>
<tr>
<td>Dysfunctional Workforce</td>
<td></td>
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</table>

From the analysis, the team found that many of the "disciplines" or practices that make up the Powertrain Production System are not in operation at plants in the Powertrain Organization. Out
of 38 PPS disciplines, 14 are being performed at a low level or not at all. For example, there is basic awareness of the concepts of Level Production and JIT, but the associated disciplines are not deeply understood or implemented. Machine reliability and Ford’s Total Productive Maintenance program (FTPM) are perceived to only impact uptime, rather than being the enabler of other disciplines. Most In-Station Process Control (on-line quality techniques) and people approaches are “piecemeal, with underachieving results.”

<table>
<thead>
<tr>
<th>Machine Reliability</th>
<th>In-Station Process Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTPM</td>
<td>Dynamic Control Plan (DCP)</td>
</tr>
<tr>
<td>Reliability &amp; Maintainability</td>
<td>Advanced Quality Planning (AQP)</td>
</tr>
<tr>
<td>Total Maintenance System</td>
<td>Status Boards &amp; Marquees</td>
</tr>
<tr>
<td>Bottleneck Analysis</td>
<td>Manage the Change</td>
</tr>
<tr>
<td></td>
<td>Supplier Involvement</td>
</tr>
<tr>
<td></td>
<td>Scheduled Tool Change</td>
</tr>
<tr>
<td></td>
<td>Mistake Proofing</td>
</tr>
<tr>
<td></td>
<td>Customer Complaint System</td>
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<td>Standardized Work</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Just-in-Time</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Handling &amp; Layout</td>
<td></td>
</tr>
<tr>
<td>Quick Changeover</td>
<td></td>
</tr>
<tr>
<td>Packaging Methods &amp; Standards</td>
<td></td>
</tr>
<tr>
<td>Inventory Control System</td>
<td></td>
</tr>
<tr>
<td>Transportation Management</td>
<td></td>
</tr>
<tr>
<td>Total Supplier Performance</td>
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</table>

<table>
<thead>
<tr>
<th>Level Production</th>
<th>People</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule Stability</td>
<td>Survey of Attitudes</td>
</tr>
<tr>
<td>Balanced Capacity</td>
<td>Rewards and Recognition</td>
</tr>
<tr>
<td>Daily Schedule Attainment</td>
<td>Resource Planning</td>
</tr>
<tr>
<td>Continuous Flow</td>
<td>Job Rotation</td>
</tr>
<tr>
<td>Batch of One</td>
<td>Suggestion Programs</td>
</tr>
<tr>
<td>Daily Review of Customer Perf.</td>
<td>Problem Solving</td>
</tr>
<tr>
<td></td>
<td>Employee Relations</td>
</tr>
<tr>
<td></td>
<td>Project Management</td>
</tr>
<tr>
<td></td>
<td>BIC Selection</td>
</tr>
<tr>
<td></td>
<td>Policy Deployment</td>
</tr>
<tr>
<td></td>
<td>Empowerment and Teamwork</td>
</tr>
<tr>
<td></td>
<td>Training</td>
</tr>
<tr>
<td></td>
<td>ISRS 5-Star &amp; Ergonomics</td>
</tr>
</tbody>
</table>

In general, the current state processes are reactive instead of proactive. Responsibility in the traditional structure is placed in functional chimneys, rather than accomplished through teamwork and empowerment at the lowest level. In terms of barriers to successful implementation of the PPS methods, people's resistance to change is the highest risk factor to overcome.
The recommendations from the committee who performed the current state analysis were as follows:

1. Accelerate FTPM (Ford Total Productive Maintenance) - This program provides a foundation for initiating other lean production methods, and also introduces small group activities, workers operating in teams to solve problems.

2. Increase communication of FPS activities to the union and plant operating committees. This allows one to address concerns from these groups, and begins the mindset shift which will be required.

3. Training is needed to develop the new skills required, and to lay a foundation for the design and engineering methods needed for lean manufacturing.

2.2.3 Cleveland Production System

One of the early Ford examples of lean production is the production system used at Cleveland Engine Plant. This system is a precursor to the Powertrain Production System, and was used as an internal benchmark in the design of FPS. This system is a good example because it illustrates what can and can’t be done relative to changing one part (one plant) of Ford’s system.

Table 2-3 Elements of the Cleveland Production System

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Description</th>
</tr>
</thead>
</table>
| Focus on Cost       | Total costs vs. operating costs  
                        | Life-cycle costs  
                        | Focus on Value-added vs. non-value added activities |
| Focus on Time       | Less time is the “foundation” of lean manufacturing  
                        | Physical plant layout design: minimize conveyance, buffers, repair bays, inventory storage  
                        | Quick changeover to be flexible to customer demands  
                        | Material handling, Kanban (pull system) |
| Level Production    | Improve throughput time (Manufacturing Cycle Time)  
                        | Improve equipment reliability (using TPM)  
                        | Look at entire value-chain, focus on customer satisfaction |
| Zero-Defect System  | Source of errors addressed by mistake-proofing devices  
                        | Defect information is replaced by error information  
                        | Developed by operators |
The Cleveland System focuses on the elements listed in Table 2-3. The strength of this system lies in clearly stating the important priorities of the organization. Each of the main objectives is addressed by a specific list of elements. The goal of level production, for example, is considered a result of such actions as improved machine reliability and cycle time. In Chapter 4, we treat these overall system objectives as functional requirements, on which the manufacturing system design is based.

A weakness in Cleveland's system, and in the Powertrain system which is similar, is that this is a depiction of a production system from the viewpoint of a plant only. It does not consider the systemic changes necessary to fundamentally change the manufacturing function within Ford. For example, the links between sub-suppliers to first tier suppliers, and from these suppliers to assembly plants could not be fully developed by a single manufacturing site. A single plant can only achieve so much without the support of other parts of the organization: suppliers, product development, management systems, etc.

2.2.4 FPS Components and Timeline

Based on the vision statement and on the evaluation of the current state of manufacturing at Ford, the FPS team developed a model of the production system. The first step was to develop a set of principles or rules to run the manufacturing operations. Table 2-4 describes these principles and "stretch objectives", Ford's term for the corporate goals or overall metrics they wish to achieve.
Table 2-4  Ford Production System Principles and Objectives

<table>
<thead>
<tr>
<th>Principles</th>
<th>Stretch Objectives</th>
<th>Measurables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Workgroups</td>
<td>• &gt;99% Successful/90% Satisfied</td>
<td>• % Effective</td>
</tr>
<tr>
<td></td>
<td>• &lt;10.0 Occupational Severity Rate</td>
<td>• % Satisfied</td>
</tr>
<tr>
<td></td>
<td>• Zero Fatal Injuries</td>
<td>• Safety and Health Assessment Review</td>
</tr>
<tr>
<td></td>
<td>• 100% Compliance with Common Audit Process</td>
<td></td>
</tr>
<tr>
<td>Zero Waste/Zero Defects</td>
<td>• &lt;1 Day Dock-to-Dock Time</td>
<td>• First Time Through</td>
</tr>
<tr>
<td></td>
<td>• No Defects Made</td>
<td>• Dock-to-Dock Time</td>
</tr>
<tr>
<td></td>
<td>• No Defects Passed On</td>
<td>• (and Value Added %)</td>
</tr>
<tr>
<td>Align Capacity with Free Market Demand</td>
<td>• &gt;95% Built to Market Demand</td>
<td>• Build to Schedule</td>
</tr>
<tr>
<td></td>
<td>• &lt;10 Controlled Commodities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• &lt;15 Days Order to Delivery</td>
<td></td>
</tr>
<tr>
<td>Use Total Costs as Drivers</td>
<td>• Achieve Affordable Business Structure Targets</td>
<td>• Total Cost per Unit</td>
</tr>
<tr>
<td>Optimize Production Throughput</td>
<td>• 33% More Capacity from Existing Sites</td>
<td>• Overall Equipment Effectiveness</td>
</tr>
</tbody>
</table>

To elaborate on some of these elements:

- Zero waste and defects incorporates the idea of improving quality, reducing lead times, inventory, and eliminating activities that do not add value to the product.

- Using total costs as a driver refers to looking at the total cost of running plants, to make an effective tradeoff between the costs of labor, equipment, material, quality, shipping, inventory, etc. The objective of meeting "affordable business structure targets" recognizes that the price Ford targets is a function of the marketplace and not determined by the plant, so the business focus should be on reducing costs.

- To optimize throughput, Ford plans to use Total Productive Maintenance (TPM) and machine reliability improvement methods to increase the capacity of existing manufacturing sites.

These principles and objectives represent what Ford believes would indicate an acceptable level of progress towards achieving the FPS vision. The measurables are the set of performance metrics which will be the primary means of judging manufacturing performance, and will be discussed further in Chapter 3.
2.2.5 FPS Model

A graphical model was developed as shown in Figure 2-3. It provides an overview of the Ford Production System and defines the different areas which will support the manufacturing and assembly operations:

1. The engineering system includes the supporting activities of product and process design, plant design and layout, and manufacturing process launches.

2. The material flow system includes the scheduling of customer orders to provide stable releases and synchronous material flow.

3. The plant operating system focuses on providing industrial materials, maintenance, changes to the human resource system, and the quality operating system to guarantee part consistency. This part of the model also encompasses changes to the management process: management by total cost, capacity planning, etc.

![Figure 2-3 Ford Production System Model](attachment:figure23.png)

The model in Figure 2-3 indicates that these subprocesses all support the plant floor operations to meet the FPS vision, principles, and stretch objectives. Two elements that form the foundation of changes in the manufacturing plants are FTPM and the manufacturing measurables. FTPM is
critical because machine reliability has been judged to be a key success factor and because it creates a work team orientation. The measurables are important for aligning objectives and evaluating progress.

Some other important points of the model:

- The three separate areas of engineering, material flow, and plant operating systems are not integrated.
- Quality falls under the Quality Operating System, a process already in place in several divisions to track in-plant and customer quality issues. This system is also not closely integrated with the FPS model.
- This model does not describe which components can be managed within the plant and which are controlled outside of the plant.

These points led the management of FPS to create a new model to emphasize the integration of activities that will be required. Though still under development and not described in detail here, the new model focuses on the subprocesses which are the direct responsibility of the plant, and groups other important elements into three categories which support the plant subprocesses:

1. Partner Relationships with Suppliers
2. Robust and Compatible Products and Processes
3. Integrated Corporate Processes (i.e., capacity planning, program management, etc.)

2.2.6 Plant Operating System Details

The details of the lean production processes that Ford plans to introduce in all manufacturing sites are not fully identified or defined. This will take place over the next several years. Most of these will be developed based on best operating practices currently in place at plants or divisions around the company. Groups at Ford have been studying lean production techniques since the early 1980's, as the Cleveland Production System example indicates, so there are examples of good applications available. Table 2-5 illustrates some planned actions, along with potential issues, based on the analysis of Ford's Powertrain Production System, and using this system's five process categories.
<table>
<thead>
<tr>
<th>Category</th>
<th>Planned Action</th>
<th>Issues &amp; Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level Production</td>
<td>Implement FTPM</td>
<td>- Uptime</td>
</tr>
<tr>
<td></td>
<td>Part Commonality</td>
<td>- Quality defects</td>
</tr>
<tr>
<td></td>
<td>Quick Changeovers</td>
<td>- Training</td>
</tr>
<tr>
<td></td>
<td>Match Capacity to Forecasted Demand</td>
<td>- Poor layouts</td>
</tr>
<tr>
<td>Just-In-Time</td>
<td>Cross-Functional Workgroups</td>
<td>- Long changeovers</td>
</tr>
<tr>
<td></td>
<td>Implement FTPM</td>
<td>- F&amp;T constraints</td>
</tr>
<tr>
<td></td>
<td>Lean Layout Concepts</td>
<td>- Capacity Planning Process</td>
</tr>
<tr>
<td></td>
<td>In-house Replenishment System</td>
<td>- Inaccurate Forecasts</td>
</tr>
<tr>
<td>Machine Reliability</td>
<td>Predictive Maintenance (proactive)</td>
<td>- Lack of machine reliability</td>
</tr>
<tr>
<td></td>
<td>Implement FTPM</td>
<td>- Supplier performance</td>
</tr>
<tr>
<td></td>
<td>Total Cost Management</td>
<td>- Excessive equipment loading</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Customer requirements not communicated</td>
</tr>
<tr>
<td>In-Station Process</td>
<td>Cross-Functional Workgroups</td>
<td>- No emphasis on prevention</td>
</tr>
<tr>
<td>Control</td>
<td>Total Cost Management</td>
<td>- Lack of empowerment</td>
</tr>
<tr>
<td></td>
<td>Standardized Processes</td>
<td>- Job classifications</td>
</tr>
<tr>
<td></td>
<td>Visual Factory Techniques</td>
<td>- Manual data analysis</td>
</tr>
<tr>
<td></td>
<td>Emphasize Concept of Zero</td>
<td>- Labor &amp; overhead system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Misuse of OEE measure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Formal program is not practiced</td>
</tr>
<tr>
<td>People</td>
<td>Demonstrate Mgmt. Commitment</td>
<td>- Inadequate Use of FMEA</td>
</tr>
<tr>
<td></td>
<td>Cross-functional Workgroups</td>
<td>- Job insecurity</td>
</tr>
<tr>
<td></td>
<td>Improve Communication</td>
<td>- Lack of accountability</td>
</tr>
<tr>
<td></td>
<td>Training</td>
<td>- Labor &amp; overhead system</td>
</tr>
<tr>
<td></td>
<td>Emphasize Cost of Current State</td>
<td>- Resource planning</td>
</tr>
<tr>
<td></td>
<td>Continue Building Joint Programs</td>
<td>- Employee skepticism</td>
</tr>
</tbody>
</table>

The issues listed in Table 2-5 summarize the difficulties Ford expects as they implement lean production. These problems are the basis for the design problem discussed in Chapter 3, which examines the measures Ford should use to support the Ford Production System.
2.3 Literature Review

2.3.1 Lean Production System Design

Summary of Key Elements

The origin of lean production dates back to Japan in the 1950's, and the development of the Toyota Production System. According to Taiichi Ohno, the founder of this system, it was "born of the need to make many types of automobiles, in small quantities with the same manufacturing process"[29]. Lean manufacturing moved the single-piece flow concepts practiced by the traditional Ford mass production system to Tier 1 and Tier 2 suppliers, in the form of cellular manufacturing methods. The supply chain was linked to enable level production. Some of the key elements that this strategy focuses on include: quality, cost, delivery, reliability, lead time, flexibility, and employee relationships [19].

Several authors have done comparisons of lean systems and traditional mass production. Womack [36] notes the following features of lean production versus typical manufacturing systems:

- no part warehouses and low inventory, vs. using inventories to smooth production
- less plant space, vs. extra space for part repairs
- balanced work tasks, vs. a large number of indirect employees
- defective parts are sent to Quality Control by operators, vs. using incoming inspection to detect bad material from suppliers
- quality is ensured at each step, vs. quality can happen at the end of the line.

In lean systems, eliminating waste becomes a common goal for everyone in the plant. All activities that do not add value to the product are reduced or eliminated through continuous improvement. The seven wastes in the Toyota Production System include wastes caused by overproducing, waiting, transporting, processing, unnecessary inventory, unnecessary motion, and producing defects. Overproduction is considered the worst of the seven, as it hides the other wastes. In Toyota's system, the automation of non-value-added tasks such as the transportation of materials is also a waste. Buffers are considered wasteful. As Ohno states, "there is nothing more wasteful than producing something you don't need and storing it in a warehouse. Both
people and machines are wasted, and the warehouse puts your money to sleep"[23]. Inventories can also hide quality defects.

Time is another wasteful element that lean systems try to control. The reduction of lot sizes allows you to shorten lead times, and create some other benefits: a level demand for component parts, steady capacity requirements and fewer unpredictable bottlenecks, and a reduced need for safety stock [19]. Reduced changeover times of equipment are therefore required to make smaller lot sizes economical.

As Maskell notes [19], large Work-in-Process inventories and part shortages require extensive production planning processes and careful master scheduling. Local scheduling of production allows workers to make more production decisions without going through a time-consuming loop for management approval [29]. Having operators perform the scheduling also increases their commitment. Worker flexibility is also important. Disruptions of the part flow can be eliminated if workers are able to move to work stations with the most severe bottleneck. Factory layouts are changed in lean systems. They are organized by product to minimize handling and allow continuous flow.

Other differences include using group technology for processes and products, such as the strategy used by Kawasaki to eliminate changeovers by dedicating welding lines to a particular model [23]. Part design can be improved to reduce large part inventories and the need for inflexible equipment and tooling.

Some authors have looked at the system design requirements for lean production versus traditional systems. Black [2] describes five different manufacturing system designs: the job shop, flow line, linked-cells, project shop, and continuous process. Most factories are mixtures of the job shop and flow line systems, with several job shop operations feeding assembly lines. As the flow line gets large, it is called mass production, and consists of specialized equipment, dedicated to one product, typically with one machine of each type. Line balancing is done to balance the flow, and the facilities are arranged by the sequence of product operations. Setup times are long, and the system is not very flexible.
The problem with the traditional design is that line performance is stressed instead of system performance. Buffers between areas compensate for disruptions. A typical lean producer might reconfigure the job shop and flow lines into manufacturing cells to address these issues.

Another problem with traditional manufacturing is in the use of information for planning instead of control of the process [3]. Production information will typically be reported to management rather than used at the plant level. Forecasts using this information often assume levels of downtime and defects, for example, and modify the quantity that needs to be produced rather than addressing the cause of disruptions.

Examples in Industry

Adler [1] provides a good description of an application of lean production techniques in North America - the General Motors and Toyota joint venture NUMMI. Closely modeled after Toyota's Production System, NUMMI has been successful in many areas:

- The Just-in-Time process reduces WIP and makes quality assurance the responsibility of each work station. Each machine is designed to detect defects and malfunctions automatically (autonomation).
- Kaizen (continuous improvement) at NUMMI includes an active suggestion program, with 10,000 suggestions submitted in 1991, and 80% of these implemented.
- Job rotation is standard, workers are cross-trained, and the job classification system has been simplified.
- Planned leveling of production eliminates variation in the daily and weekly schedules.
- Standardized work improves safety, quality, control of inventory, and makes job rotation easier, as well as making it quicker to change the plant to a new line speed.

Other authors have looked at how to avoid failures in the launch of lean manufacturing methods. Walker [35] notes that Japanese manufacturers typically invested 10 years of consistent effort to see an "improvement culture" become ingrained in the workforce. If an infrastructure does not develop to support new practices, for example, "TQM [Total Quality Management] will soon die out after a few successes." A good example is in the application of "quality circles" in many U.S. firms in the 1980's, where management typically passed the responsibility for quality issues
to the workforce alone. As Deming and others have agreed, the majority of defects are caused by dysfunctional work systems and processes and practices installed by management.

There are numerous studies which outline the key components of lean systems. As summarized by Maskell, lean production is a highly disciplined system. It requires a skilled workforce, management commitment, and "excellence in every area of the process"[19].

2.3.2 Performance Measurement

*Performance Measurement as a Design Problem*

One general observation of performance evaluation is that measurement drives human behavior. Another way to phrase this is, as Peter Senge notes, a system responds to how it is measured [26]. When measurables adversely affect a system it results in "creative tension," which impacts a person when he attempts to do the right thing at the expense of his metrics. It is therefore important to incorporate the appropriate measures of system performance into the design process.

As Sink [28] describes, "performance measurement system development is not often looked upon as a design problem." System approaches are not common; a typical approach will be to modify current systems or "buy a tool off the shelf." He states that much of the controversy and lack of acceptance of measures comes from attempts to make a complex systems problem too simple.

Some authors have looked at measurement design from the perspective of satisfying a set of general criteria. Globerson [21] states that you should consider measurables which satisfy the following:

- are chosen from the company's objectives
- make possible comparison of other organizations
- the purpose of each criterion is clear
- data collection is clearly defined
- ratios are preferred to absolute numbers
- should be under the unit's control
- are objective instead of subjective
Other authors such as Thor [33] have proposed similar lists of things a company needs to address when choosing measures:

- The usual excuse for choosing one measure is to keep things simple. Organizations need overall strategic measures, but also need local measures that can be directly affected by people doing the actual work.
- Firms often don't measure how well customer needs are satisfied. This may only be able to be measured indirectly, but is not any less important.
- People are more likely to be motivated by a measure they have had some part in selecting.
- Measures that are intended for "grass-roots feedback" should be kept at the grass-roots level, and not used for reporting.
- The firm can be thought of as a hierarchy, where each level receives the measurement feedback needed for that level of control.

Another approach in performance measurement is to measure the rate of change, or the rate of "learning," rather than focusing on a single measure such as cost, quality, or delivery [10]. One can use a "half-life curve" to measure the time it takes to achieve a 50% improvement in any output measure, to compare internal improvement rates. This measure is easy to use and may allow better comparison between groups.

**Manufacturing Applications Of Measurement**

Academic studies have also looked at the measures which are best suited for manufacturing activities. In this area, they have looked at what effect the choice of performance metrics has on specific manufacturing issues.

Maskell [19] has developed some general rules for choosing manufacturing measurables:

- measures should be non-financial, as financial numbers are not applicable to daily operations
- there should be variation among locations, as each area has different things that are important to focus on
- measures should change over time, as the needs change
- ratios should not be used, as they have no tangible meaning, creating confusion
measures should foster improvement versus monitoring operations

Other authors add some additional rules for the development of measurement systems for manufacturing [12]:
- the measures should be related to customer-driven critical success factors
- measures should promote intrafunctional communication so the total system performance of the business is optimized
- there should be feedback between one's own performance and the best-in-class performance
- the number used at one time should not be limited

Some key manufacturing measures to track are productivity and quality. As Goldratt states in *The Goal*, the fundamental means of improving manufacturing operations is to increase total throughput and decrease total operating expenses [13]. Productivity can be defined as total output divided by the required input of all factors, such as labor, materials costs, etc., and total versus partial productivity should be measured. For example, labor productivity should measure total output of product divided by total headcount, not actual labor hours versus standard or budgeted hours [12].

Typical quality measures for controlling a process include scrap, defects, rework, extra inspection, troubleshooting time, quantity of bad material, and unscheduled maintenance time [32]. The costs of quality - prevention, appraisal, and internal and customer failure costs - can also sometimes be measured. With the implementation of Total Quality Management becoming more common, some authors note greater emphasis on customer satisfaction, such as measures promoted in the Malcolm Baldrige National Quality Award [21].

*Specific Measures For Lean Production*

As discussed earlier in the chapter, lean production contains many fundamental differences from traditional mass production. It is not correct to assume that the same manufacturing measures can be used successfully in both manufacturing systems. Some authors have looked at measures which address particular elements of lean manufacturing.
Plant level measures used in the study of lean and traditional automotive manufacturers by Womack [36] include the following: productivity (assembly hours per car), quality (assembly defects per car), layout (plant floorspace per car), inventories of parts, the size of the repair area, the percentage of the workforce in teams, job rotation, suggestions per employee, number of job classes, number of training hours for new employees, and absenteeism rates.

Manufacturing Cycle Time, the average time it takes for a product to pass through the production process, from raw materials to finished goods, is a primary focus of lean producers. In a study of Hewlett-Packard, faster cycle time yielded both a quality and cost advantage. Thinking about time forced attention on all manufacturing activities [12]. As Maskell notes, long manufacturing cycle times lead to high Work-in-Process inventory (WIP), creating such negative results as less accurate forecasts, uneven loading, complex information systems, and schedule inflexibility. One easy way to approximate the cycle time is to simply count the level of WIP. Lot sizes can also be tracked [19]. Distances that parts travel can also reflect a product's use of space, as well as potential inventory levels and labor needs [18].

Flexibility is also a goal of lean production. There appears to be a lack of operational measures for this plant characteristic. One possible measure of plant flexibility is in the flexibility of personnel, in terms of the amount of cross-training [19]. This can be the average number of different tasks performed, for example. In a study by Hall [14], Allen Bradley used three measures to track the determinants of flexibility: setup times, product lead times, and the number of skills mastered per employee.

In a study of lean manufacturers, Ritzman found that the best way to cut inventory was to reduce setup time and lot size [23]. Good management of process variables such as scrap rates, worker flexibility, equipment failures, and capacity imbalances also improved inventory and delivery performance. A good product structure - fewer final assemblies, and fewer levels of assembly, for example - increased the chances for success.

A study by Garvin [11] of Japanese and American manufacturers indicated that the highest quality producers were also those with the highest output per man-hour. Plants with the lowest
failure rates evaluated supervisors in terms of defect rates, scrap rates, and amount of rework, managers in terms of warranty, and plants in terms of total cost of quality, because upper-management was able to control such things as product design and incoming materials issues. He found that the best firms used extreme precision in reporting.

In a different study of a Japanese lean manufacturer, the firm used 12 charts displayed on walls throughout the plant with the key measures [14]. The top chart displayed "total costs down," or the overall plant success in reducing costs. Other measures included average setup time per job, process time, number of defects from internal customers, percentage downtime, number of line stops per day, and amounts of inventory. The attention was devoted to these other charts, not to the total cost measure itself.

Some typical changes to measures as you move from traditional to lean production include the following [14]:

- There is an attention shift from defect counts to prevention of defects. You may start by measuring percentage of defects and move to measuring the percent of operations with fail-safe devices.
- Measurement is made of total costs, such as total payroll versus direct labor costs
- Progress tracking is done in specific programs to eliminate waste: housekeeping, setup times, batch sizes, unplanned downtime, distance work travels, number of new ideas per employee, first-inspection pass rates, space occupied, customer satisfaction indices, etc.
Summary of Performance Measurement Literature

It is clear that many studies have been done on choosing performance measurements. There is not always a consensus among authors, and likewise among different firms. As evidence that firms are unsure of what measures to use, it is common that, as companies implement new manufacturing methods, the old measures tend to persist besides the new ones, which can cause confusion [14]. In a survey by KPMG of manufacturing firms, over 50% rated the relevancy, timeliness, completeness, cost-effectiveness, and presentation of manufacturing performance measures as poor or average [21]. These findings indicate that a method of properly designing measures to support the organization’s true goals would be beneficial.
3. Ford's Measurement Design Problem

3.1 Design of Measurables for FPS

3.1.1 Measurables as a Foundation

As described in the last chapter, the manufacturing measurables are planned to be a foundation of the Ford Production System. In fact, they will be the first changes in the manufacturing arena that will be launched corporate-wide for Ford 2000. The metrics are therefore an important part of Ford's strategy. As the reengineering team continues to design the elements of the Plant Operating System in detail, the plan is to have the measures in place first, to enable these changes as they are introduced.

In developing the measurables, the objective was to find a set which had the following characteristics:

- Few in number
- Emphasize physical instead of financial measures
- Focus on trends and forecasts
- Process-oriented
- Designed for usage by both plant floor employees and management
- Common for all of Ford's manufacturing operations

One key goal was the design of a single set of measures which could be used in all types of plants and at all levels of management, including the plant floor. According to Hank Lenox, the head of the Ford Production System, a standardized set of metrics "provide consistency, and drive the themes you want to drive." As described in Chapter 4, these themes can be thought of as the functional requirements of FPS, and measurables need to be based on these requirements.

The effect on employees and managers is a top concern, and the measures are intended to supply a shared objective and improve communication between levels. Good measurables definition is also key to preventing problems experienced with existing measures, such as confusion and misreading of situations, or deliberate "tweaking" of data.
The following manufacturing measurables were developed:

- Safety and Health Assessment Review Process (SHARP) - a detailed evaluation of the health and safety related processes at a facility.

- Attitude Surveys - not completely defined, this measure will track employee attitudes about their jobs and conditions that affect their ability to perform.

- First Time Through Capability (FTT) - the percentage of units that complete a process without being scrapped, retested, rerun, returned, or diverted to an off-line repair area.

- Total Dock-to-Dock Time (DTD) - the elapsed time between the arrival of raw materials and the release of finished goods for shipment, for a particular control part.

- Build to Schedule (BTS) - an index of the percentage of units scheduled for a given day that are produced in the correct sequence on that day.

- Overall Equipment Effectiveness (OEE) - a composite index of the availability, performance efficiency, and quality rate of a given piece of equipment (the constraint operation).

- Total Cost - the total cost per unit of material, labor, overhead, freight, inventory, and other associated plant costs.

The following sections describe the current measures used at Ford and the design process used to develop the FPS measures.

3.1.2 Current State of Measurement at Ford

All of Fords plants are tracking some key measurements in some general categories of importance, such as quality, delivery performance, and equipment uptime. As a company, however, Ford does not currently have a standardized set of measurements that all plants use.
This not only makes it difficult to compare conditions at different plants, but can result in misaligned goals.

In many cases, a plant will have its own standard set of measurables that all managers at that site adhere to. In addition, there has been some standardization within a division. For example, the Automotive Components Division (ACD) has had very similar measures among its plants in recent years, and has developed a “datacard” or summary of a specific set of measures to be used in division-level quality reviews, as well as in managing the plant floor. In 1995, plant managers from the Vehicle Operations, Powertrain Operations, and the Electrical and Fuel Handling Division met to agree upon a large set of measures that contains all the critical information each division uses to run their businesses and can be placed in 16-panel charts. Samples of these charts are included in the Appendix. An individual plant might focus on only a small number of key measures from this set.

Table 3-1 compares the measurables used in different sets, including the ACD datacard and some measures from the 16-panel charts, as well as the FPS measurables. These measures are divided into generic categories: production (non-financial) measures, financial measures, people measures, and process measures, and some generic metrics in each category are included.
<table>
<thead>
<tr>
<th>Generic Measures</th>
<th>ACD Datacard</th>
<th>16-Panel Charts</th>
<th>FPS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production Measures</strong></td>
<td>Customer Satisfaction at 3 MIS</td>
<td>Quality - R/1000, TGW, warranty, QR's, % non-conforming material</td>
<td>First Time Through</td>
</tr>
<tr>
<td></td>
<td>Customer Evaluation Build to Schedule FCSD Perf. Evaluation</td>
<td>Volume - actual vs. schedule</td>
<td>Build to Schedule</td>
</tr>
<tr>
<td></td>
<td>First Time Through Dock-to-Dock Time</td>
<td>Inventory ($) vs. budget</td>
<td>Dock-to-Dock Time</td>
</tr>
<tr>
<td></td>
<td>Inventory (in $)</td>
<td>NP stores ($)</td>
<td>OEE</td>
</tr>
<tr>
<td></td>
<td>OEE</td>
<td>Press Down Days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Warranty</td>
<td>Premium Freight ($, # of shipments)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Customer Rejects, Returns, &amp; QR's</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Supply Base Quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Financial Measures</strong></td>
<td>Total Costs</td>
<td>Total Cost - Actual vs. Budget</td>
<td>Total Cost</td>
</tr>
<tr>
<td></td>
<td>F&amp;T Spending</td>
<td>Labor &amp; Overhead</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Key Product Line</td>
<td>Raw/Bulk Material</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cost/Unit</td>
<td>Inbound Freight</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scrap (as a % of material cost)</td>
<td>Meet Affordable Business Structure</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Overtime Hours(% and $)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Labor - plant hours/unit for top products</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Equiv. employees per stamped vehicle</td>
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<td></td>
<td></td>
<td>Facility Spending</td>
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<td></td>
<td></td>
<td>Other Costs - SUB, GEN</td>
<td></td>
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<tr>
<td></td>
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<td>Launch Costs &amp; Budget</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Cost Savings Initiatives</td>
<td></td>
</tr>
<tr>
<td><strong>People Measures</strong></td>
<td>Salaried Personnel</td>
<td>CIRS Status (suggestions)</td>
<td>Health &amp; Safety Measure</td>
</tr>
<tr>
<td></td>
<td>Hourly Personnel</td>
<td>Health &amp; Safety - Severity rate, First Time Visit, Lost Time Rate</td>
<td>Employee Surveys</td>
</tr>
<tr>
<td></td>
<td>CIRS (employee suggestions)</td>
<td>Workers Comp. ($)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Health &amp; Safety</td>
<td>Absences (%)</td>
<td></td>
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<tr>
<td><strong>Process Measures</strong></td>
<td>SPC (% of processes in Green status)</td>
<td>Die Set Time</td>
<td></td>
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<tr>
<td></td>
<td>ISO9000/QS9000 status</td>
<td></td>
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<td></td>
<td>FTPM status (checkpoints)</td>
<td></td>
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<td></td>
<td>Advanced Quality Planning</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Outside Sales Revenue</td>
<td>Obsolescence for prod. and NP parts (in $)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental Waste</td>
<td></td>
<td></td>
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</tbody>
</table>
It is clear that the list of FPS measurables is much shorter, and does not address the same number
of things that the current metrics do. A majority of the managers interviewed felt that the current
measures do not provide information that is useful to all levels of plant management or for
control of operations on the plant floor. Chapter 5 discusses the results from a survey distributed
to managers at Ford’s manufacturing sites, including a summary of comments on the current
measures being used.

3.1.3 Design Process for FPS Measures

To develop the FPS measurables, a team of manufacturing employees was assembled. Focusing
on the characteristics discussed above, the team used “best practices” around Ford as a starting
point for their development of the corporate-wide metrics:

- The SHARP measure was first examined in North American Powertrain Operations.
- First Time Through is a new measure, although similar to First Run Capability, used in
  ACD.
- Dock-to-Dock time is an extension of the Manufacturing Cycle Time measure used in
  Electronics Operations (ELO). The concept of “value-added time” is used at Toyota.
- BTS is a unique measure for delivery performance.
- OEE is a concept from the Total Productive Maintenance methodology developed by the
  Japanese Institute of Plant Maintenance (JIPM), and is a measure used in FTPM.
- The concept of the Total Cost measure has been applied in Vehicle Operations of Europe.

After developing the main concepts for the four key measures - First Time Through, Dock-to-
Dock Time, Build to Schedule, and OEE - the team performed a study of these measures in
action, by applying them at different Ford manufacturing sites. A total of twenty-four sites were
visited, eight of these in Europe and the rest in North America. The study was cross-divisional,
with ten Vehicle Operations plants (stamping and assembly), six Powertrain plants
(transmissions, engines), and eight components plants. These plant trips were mainly to prove
out the calculations and data collection required for the FPS measures, and to get feedback from
plant personnel on how applicable the measures would be in different plant environments.

Note that, although the team attempted to match the FPS measures to the general Principles and
Stretch Objectives described in Table 3 of Chapter 2, a rigorous design methodology was not
used to develop measures to meet the functional requirements of the Ford Production System. Chapter 4 discusses an approach to design measures by defining the requirements and how to satisfy these independently.

3.2 Detail of FPS Measures

3.2.1 Set of FPS Measures

This section will discuss five of the seven FPS manufacturing measures. The SHARP measure is the result of a lengthy auditing procedure of health and safety processes at each plant. The audit yields a point score, which will be tracked for each plant and indicates areas of improvement. It is not a measure that can be used to control the manufacturing system, however, so it will be ignored for the rest of the discussion. The employee surveys measure has not been fully defined, although most of the FPS management interviewed stressed the importance of people processes in the implementation of FPS.

3.2.2 First Time Through

First Time Through Capability is a measure of the percentage of parts which pass through the manufacturing process without being scrapped, retested, rerun, returned, or repaired off-line. The objectives of this measure are to monitor quality performance over time and assist in the early identification of potential quality issues. This data is intended to be collected daily for all products made in the plant, although only the value for a “control part,” a part which follows the entire manufacturing process in the plant, will be reported by plant management.

\[
\text{Equation 1 Calculation of First Time Through Measurable}
\]

\[
\frac{\text{Units Entering the Process - (Scrap + Reruns + Retests + Returns + Units Repaired Off-Line)}}{\text{Units Entering the Process}}
\]

The calculation is shown in Equation 1. The FTT percentage will be calculated for each subprocess of the product, and these will be multiplied together for an FTT of the total process. For example, a vehicle assembly operation may contain three major subprocesses: body, paint, and final assembly. The FTT will be calculated for each of these plant subprocesses, and then a total FTT will be calculated as follows:
Total Process FTT = Subprocess$_1$ X Subprocess$_2$ X Subprocess$_3$

The benefits that Ford expects from this measure are as follows:

- measures both the quality of the process and the quality of the output of the process
- reduces the need for excess inventory
- improves the plant's ability to maintain sequence of production
- lower warranty, scrap and repair costs

Some major issues that have been discussed:

- FTT uses control parts for reporting plant-level numbers. There is a possibility for "gaming" by management, where the numbers on one control part are improved but plant-wide quality does not change.
- FTT for subprocesses are multiplied together. This can give unrealistic numbers for problem solving purposes, and it becomes difficult to tie actions to results. Even for subprocesses, the FTT number is a composite of different machines, which may have individual quality issues that can become disguised by a single measure.
- Plant-wide numbers are calculated using a cost-weighted average. Some managers have expressed concern about the usefulness of a plant-wide average for making quality improvements.

3.2.3 Dock-to-Dock Time

The Dock-to-Dock Time Measurable (DTD) tracks the elapsed time between the arrival and unloading of raw materials and the shipment of finished product. This measure is similar to Manufacturing Cycle Time (MCT), but includes not just the time parts spend in the process, but the buffers before and after manufacturing. Like FTT, a control part is used to indicate the progress of all parts made in the plant.

The calculation is shown in Equation 2, and is simply the time it would take for all parts in the plant to have passed through the process based on the end-of-line pack rate. Dock-to-Dock time is thus another measure of lead-time or Work-in-Process (WIP) inventory levels. The FPS measurables process asks the work force to determine the components of this DTD time, performing a value added/non-value added analysis to determine wastes in the system.
Total Dock-to-Dock Time = \frac{\text{Total Number of Units of the Control Part}}{\text{End of Line Rate}}

**Equation 2  Calculation of Total Dock-to-Dock Time**

This measure is intended to focus improvement efforts on eliminating such waste as excess inventory and unnecessary material handling or processing steps. This should improve quality due to less material handling damage, lower material handling costs and space requirements, and lower inventory costs. The FPS team thinks that the DTD measure is an improvement over MCT because the inclusion of other inventories better supports the FPS order to delivery goals.

Perhaps the greatest issue with DTD is that inventory requirements can largely depend on things outside of the plant or area's control. The ability to reduce DTD time will be the result of improvements in such things as quality, uptime, flexibility, and setup times. This measure also gives the same time penalties for both raw materials and finished goods inventories. Also, it may still be possible to create "JIT warehouses" outside of the measured inventories with this system.

**3.2.4 Build to Schedule**

The Build to Schedule (BTS) measure is the percentage of units scheduled for a particular day that are produced on that day with the correct sequence. Initially, this measure is for plant end-

\[
\text{Volume Performance} = \frac{\text{Actual Number of Units Produced}}{\text{Scheduled Number of Units}}
\]

\[
\text{Mix Performance} = \frac{\text{Actual Number of Units Built to Mix}}{\text{Actual Number of Units Produced}}
\]

\[
\text{Sequence Performance} = \frac{\text{Actual Number of Units Built to Schedule}}{\text{Actual Number of Units Built to Mix}}
\]

\[
\text{Build to Schedule} = \text{Volume Performance} \times \text{Mix Performance} \times \text{Sequence Performance}
\]

**Equation 3  Build to Schedule Calculation**

43
items only and not in-process operations. As Equation 3 shows, BTS is an index made up of three separate ratios, for the percentage of the correct volume, mix, and sequence produced. Volume performance measures only the quantity built to the actual schedule. Mix performance measures the number of units of each different part type that is built on the scheduled day of production. Sequence performance measures the percentage of parts built in the exact order scheduled.

Some issues that have been discussed about this measure include the following:

- BTS does not measure actual on-time delivery or internal/external customer satisfaction with the timeliness of orders.
- The overall BTS calculation couples the components of volume, mix, and sequence by multiplying these terms together. This coupling confuses the trend in the data, and makes it difficult to measure improvement or use the BTS measure for problem solving.
- There is essentially no penalty for overproduction, as long as mix and sequence goals are met. The overall BTS number is “dominated” by the sequence term. Multiplying the subcomponents together, the overall BTS is just the number of units built in sequence as a percentage of total units scheduled, as shown below:

\[
\text{BTS} = \frac{\text{(Actual Number of Units Built to Sequence)}}{\text{(Scheduled Number of Units)}}
\]

Few plants are currently operating to build in a particular sequence, and for some components plants the concept is still undefined. The BTS measure is thus an inadequate metric for controlling the build performance of most Ford operations.

### 3.2.5 Overall Equipment Effectiveness

Overall Equipment Effectiveness (OEE) is an overall measure of equipment performance, including quality, availability or uptime, and performance efficiency or speed ratio. This measure was developed and recommended as a TPM indicator by the Japanese Institute of Plant Maintenance (JIPM), and has been in use in some Ford plants for at least five years. The OEE is intended to be used for the constraint operation of the plant only, so does not need to be reported at the plant level for all equipment.
The methodology for improving OEE falls under Ford’s Total Productive Maintenance Program (FTPM). Benefits from improvements in the OEE measurable come from improved predictability, more stable processes, better BTS performance, lower rework and scrap costs, and higher throughput.

\[
\text{Availability} = \frac{\text{Operating Time}}{\text{Net Available Time}}
\]

\[
\text{Performance Efficiency} = \frac{\text{Ideal Cycle Time} \times \text{Total Parts Run}}{\text{Operating Time}}
\]

\[
\text{Quality Rate} = \frac{(\text{Total Parts Run} - \text{Total Defects})}{\text{Total Parts Run}}
\]

\[
\text{OEE} = \text{Availability} \times \text{Performance Efficiency} \times \text{Quality Rate}
\]

**Equation 4 Calculation of Overall Equipment Effectiveness**

The calculations are described in Equation 4, with the following definitions:

- Net Available Time is the time that the equipment is planned to operate (i.e., total scheduled time minus lunch and breaks).
- Operating Time is the Net Available Time minus all downtime, such as equipment failures, setup time, adjustments, and scheduled maintenance.
- Ideal Cycle Time is the design cycle time of the equipment, or the best time ever achieved on that equipment if greater than the designed time.

OEE is often debated at Ford, and some major issues include the following:

- Availability is the sum of equipment downtime, including setup times, startup losses, etc. This measure is not easily broken down into subcomponents, and is thus hard to use for continuous improvement activities.
- OEE focuses on production volume and speed rather than quality. For example, the measure seems to allow for a percentage of scrap and defects. It does not focus on correcting the root cause of these defects.
• This measurable assumes one identifiable constraint per product in a plant. In a closely balanced operation, the correct application of OEE is not clear. There is also not a focus on improving machine reliability on equipment that is not typically constraining production but has the potential to do so.

• OEE uses a different quality rate calculation than the First Time Through (FTT) measurable. The OEE quality rate looks only at total defects, and does not include reruns, retests, or repairs, for example.

From the calculations above, the OEE expression can be simplified as follows:

\[
OEE = \left( \frac{\text{Operating Time}}{\text{Net Available Time}} \right) \left( \frac{\text{Ideal Cycle Time} \times \frac{\text{Total Parts Run}}{\text{Operating Time}}}{\text{Good Parts}} \right)
\]

\[
OEE = (\text{Ideal Cycle Time}) \times (\# \text{ of Good Parts}) / (\text{Net Available Time})
\]

In steady plant operations, the ideal cycle time and net available time are constant for a given time period, so that OEE is directly proportional to the number of good parts produced. Although this measure is impacted by machine downtime, reject and scrap levels, and machine speed, it can also be affected by starving and blocking of the machine. If the time interval for calculation and reporting is long, it is difficult to use the OEE components to control the process.

As another example, the OEE losses include setup time, so that an improvement of setup times increases the availability ratio. The OEE measure may go up or down in a period due to such things as downtime or a different product mix, which can cloud improvements in the measure of setup time.

3.2.6 Total Cost

This measure is left out of the analysis in this thesis for the most part. The managers designing FPS believe this metric is important, and the transition to a total cost system will be a radical change in running the business. However, the process of reporting and using the total cost measure to run manufacturing operations has not been fully defined.
The plan for total cost is that it will be on the "report card" for the entire company. Plant management and product management will be on the same team and driven to a common goal. This measure is replacing Labor and Overhead figures in the performance evaluation of plant management in 1996.

3.3 Plan for Using Measurables

3.3.1 Reporting Process Overview

The FPS measurables were launched in the fall of 1995. The mandate is for all plants to implement these measurables in 1996, and plant management will be evaluated on these metrics starting in July of that year. There is not an option in the current plan to change these measures or to change the way they are calculated. During 1996, the FPS measures will be incorporated into current management reporting processes in the different divisions: the 16-Panel Charts and the QOS process of ACD, for example.

The measurables design team does not believe the goal should be to compare plants. Plants in different divisions produce vastly different products, and can therefore expect different values of lead time, obtainable quality, etc., although all plants are still charged with pursuing the same stretch objectives. The initial plan is to determine a baseline for the current state at each plant, and focus on an improving trend within that plant. It has been noted that some of the measures are composite indexes, with no physical meaning, so the improvement trend becomes the main purpose of these metrics.

The plan is for the plants to initially focus on the concept behind the measures, and to determine which areas to concentrate on for their individual sites. The plants should not wait for Ford's lean production initiatives to be launched, but should take action with their own initiatives. Ford sees the fundamental problem as getting managers to buy-in to the new metrics, and building a culture that fosters their use. For example, by forcing management of powertrain and components plants to adopt the BTS measure, you encourage them to think in terms of building to an order-based sequence, which will facilitate sequencing of final vehicles at the assembly plants.
3.3.2 Plan to “Cascade to the Shop Floor”

Ford is launching the FPS measurables to use on the plant floor, as a tool for the operators. The eventual group of users for this measurement information will be all of the company’s employees. The intent is not to have the people on the floor just report these numbers, but to use the data for problem solving and improvements.

The training for the FPS measures has been designed this way. Measurables coordinators and plant champions have been assigned from every manufacturing plant in the company. Each of these contacts have received training in the fall of 1995 on the details of the FPS measures, and are charged with implementing the plant data collection process over the first six months of 1996.

Most of the data will be collected manually at first. This will help “work the bugs” out of the manual collection process, and allow Ford’s information systems departments to design automated collection methods. Part of this challenge is to integrate existing plant floor information systems, which vary widely between divisions, and have not tended to be cross-functional.

A software system has been developed to allow management to report plant-wide data to a central database, which can be reviewed by operations managers and plant management. These data are compiled on a monthly basis, and is therefore intended for reporting of overall progress of the plant's process improvements, rather than control of day-to-day operations. The details of the information process at the plant floor level are currently being designed.

3.4 Design Issues

3.4.1 How do the Measurables Support Lean Production?

Ford has made clear that its goals for the Ford Production System are to implement lean production at the company. This involves primarily shortening the lead-time from customer orders to the delivery of products and receipt of payment. The concept to follow is an overall process that is fast relative to the traditional mass production system currently in place.
The primary question addressed by the remaining chapters of this thesis is how well the FPS measures that Ford has developed and launched support the company’s goal of lean production. These sections examine the objectives for the measurables and look at what the measurement system should be expected to do.

3.4.2 Changes Required to Reach Lean Production

This thesis uses the information presented about FPS in the previous chapter and looks at two questions: Where does Ford think it currently stands on each of the elements of FPS, and what does the implementation plan look like? The goal is to find where Ford needs to concentrate first to change from the current production system to lean production.

One thing Ford has done is to benchmark itself versus what is known of the Toyota Production System. Toyota's system is based on the "foundations" of skilled, multi-functional workers using a standardized work process. The Toyota Production System emphasizes highlighting and eliminating waste throughout the manufacturing system. Its operating procedures are based on two concepts: Just-In-Time and autonomination or "built-in quality." A summary of their goals includes:

- Shortening the time it takes to convert customer orders to vehicle deliveries.
- Arranging the entire sequence in a single, continuous flow.
- Continuously finding and implementing ways to shorten this sequence and to make it flow more smoothly.

Ford's lean production approach is based on the FPS principles and stretch objectives. There is primarily a speed focus, and the key stretch objectives are a "1-day Dock-to-Dock time," "15-day Order to Delivery process," and a "24-month car" or product development process. The main foundations are the FPS measurables and FTPM, which Ford hopes will instill a quality/reliability mentality and create a team orientation.

The company wants to develop a lean production system quickly, in one year, far faster than Toyota. According to the FPS management, it has "adopted for the most part all of Toyota's concepts." On the order of 20% of plants will launch the main set of Plant Operating System initiatives in 1996.
The managers of FPS seem to agree that the workforce is a critical part in the success of POS. Workgroups and teams are functioning well in only 20% of plants currently, and this element is the most important for obtaining improvements in machine reliability and product quality. The FPS managers believe that the union generally sees the benefits FPS will provide in growth and job security, but they need to convince the union to take on a leadership role in creating the team environment.

For the structure of FPS, Ford seems to know what they want to do. They currently have a lot of ill-defined solutions: the elements of the Plant Operating System that they wish to implement may be in use in some form as a "best practice" at the company, but they have not yet been developed to meet the needs of the whole organization. Still, Ford has gone into details on some of these solutions, such as In-Line Vehicle Sequencing, the system which sequences assembly production and holds component deliveries to this sequence. These detailed solutions were not necessarily matched to the functional requirements of FPS. The measurables developed to control this system have also been detailed without matching these to the requirements. The measures were designed on a set of characteristics such as being non-financial, few in number, and common for all plants instead of being developed to support the elements which comprise FPS. The remaining chapters will address this problem.

3.4.3 Design Methodology for Performance Metrics

A goal of this thesis is to look at the processes which firms can use to design metrics to meet their goals. As the literature review in Chapter 2 indicates, authors have proposed some criteria to consider when choosing metrics and some general rules, but few studies of performance measurement have proposed a framework for designing metrics to meet specific organizational goals.

Chapter 4 examines how the methodology of Axiomatic Design can be applied in this case. Ford's aspirations for its lean production system design are discussed, and functional requirements for this system developed. The measurables are looked at in terms of how well they support these requirements, while maintaining their independence and minimizing the information required.
One methodology is to first define the functional requirements of the problem that Ford faces, and then define measurables for all of these functions. As Cochran states, the need is a commonly understood objective function within an organization [3]. The measurables design therefore needs to satisfy a multi-dimensional objective function. Rather than meeting a set of characteristics such as being few in number, process-oriented, etc., the measurables design should accomplish such functions as external reporting, performance evaluation, operations control, and influencing employee behavior. This concept is addressed in Chapter 5.

Another methodology that can be used involves matching the measurables design to Ford's implementation plan, the steps that will be required in implementing lean production techniques throughout the company. Chapter 6 looks at the steps that lean producers such as Toyota have followed to develop their production system, and examines how the FPS measurables correspond to this process.
4. Axiomatic Design Analysis

4.1 Overview of Axiomatic Design Tool

4.1.1 General Axiomatic Design Theory

As one technique for the evaluation of Ford's measurables design, this thesis will use the axiomatic design methodology. Axiomatic design is a logical process for developing the design of systems, products, organizations, etc., based on two axioms: maintaining functional independence and minimizing complexity. The design axioms were developed by Suh [30] and are fundamental truths which have been generalized from good design practices. Adhering to these axioms and the theories and corollaries derived from them has shown to consistently yield better designs. The goal of this methodology is to reduce or eliminate functional coupling of the design features, and this can be applied to product and process design, as well as system or organizational design.

![Diagram of Four Domains and Mapping Process](image-url)
Axiom 1  The Independence Axiom
Maintain the independence of Functional Requirements (FR's).

Axiom 2  The Information Axiom
Minimize the information content.

The process of axiomatic design is portrayed in Figure 4-1. It first involves deriving a set of functional requirements from the needs that customers have expressed. From these FR's, a proper set of DP's are chosen which satisfy the design axioms. The FR's can be considered what you want to do, and the DP's are how you want to accomplish it. A similar procedure is used for process design, where an optimum set of PV's is chosen to satisfy the design parameters. The axiomatic design methodology includes a process of decomposition, breaking the FR's and DP's into a hierarchy. This simplifies the design process by allowing the designer to examine only small parts of a large problem at any one time.

4.1.2 Sample Application

To illustrate the use of the first design axiom, the example of a common device such as a water faucet can be investigated. The diagram in Figure 4-2 examines a typical "old-fashioned" faucet design solution.

![Diagram of axiomatic design](image)

Figure 4-2 Sample Application of Axiomatic Design

The first step involves the mapping of the top-level functional requirement to the design parameter in the physical domain. At the highest level, the requirement is to deliver water, and
the device which will accomplish this is a faucet. Before developing the faucet design further, one needs to go back to the functional domain and decompose the functional requirement. The FR's at the next level of the hierarchy are to control both the flow rate and temperature of the water. Naturally, the user would like to control these functions independently, and a good design will accomplish this.

Figure 4-2 indicates the design parameters chosen to satisfy the FR's for controlling temperature and flow rate: separate valves are used for hot and cold water. A design equation can be developed to illustrate the relationship between the FR's and these DP's, as shown below:

\[
\begin{bmatrix}
FR_{11} \\
FR_{12}
\end{bmatrix} =
\begin{bmatrix}
X & X \\
X & X
\end{bmatrix}
\begin{bmatrix}
DP_{11} \\
DP_{12}
\end{bmatrix}
\]

The X's in every cell of the matrix in this equation indicate that adjusting DP_{11} has an effect on both the temperature and flow rate, as does adjusting DP_{12}. The design is clearly a coupled design, and requires many adjustments of both valves to obtain the desired flow rate and temperature.

A better design might use a single knob, which is turned to adjust the water temperature to hot or cold and lifted up or down to adjust the flow of water. These lever motions are the revised DP's. The resulting design equation is shown below, and the diagonal matrix indicates that this is an uncoupled design.

\[
\begin{bmatrix}
FR_{11} \\
FR_{12}
\end{bmatrix} =
\begin{bmatrix}
X & 0 \\
0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{11} \\
DP_{12}
\end{bmatrix}
\]

This is a simple example, but illustrates the concept of choosing a design which makes the functional requirements independent. In more complex system designs, the functions may never be completely independent, but the objective should be to reduce the dependence, making the system easier to operate and improving its ability to satisfy the customer needs.
4.1.3 Application to Manufacturing System Design

The concepts outlined in the sample application can be applied to any general design problem. The key to design is decision-making, and the axiomatic design methodology allows one to communicate to others what the design is, and what the design is based on. Suh outlines the steps involved in the "design loop":

1. Define FR's to satisfy the perceived needs of the customers of a system.
2. Design a physical entity to satisfy the FR's.
3. Analyze the proposed design.
4. Build a prototype, and compare the design to the original customer needs.

These four steps are iterative, and are repeated as necessary to develop an acceptable design. In the case of a part design, the prototype would be a physical element. For system design, graphical models or simulations can be used to check the feasibility of the design, but "nothing replaces the real thing in systems dealing with people"[30].

For the design of manufacturing systems, the axiomatic design methodology can be used to describe how materials are transformed into final products, by specifying the processes and part management systems involved. The methodology follows a logical process of matching goals with design parameters, and is more structured than a consensus-based method of decision-making, or "designing by brainstorm" [31].

A good initial design is critical for large organizational systems. As Suh states, the selection of a proper set of design parameters is important, "since the inclusion of insignificant items requires extensive calculations without providing useful insight, and the exclusion of an important parameter may produce erroneous results." Some common design mistakes include trying to satisfy the many FR's of a large system with an insufficient number of DP's, and defining DP's and PV's without fully defining the FR's as a first step. A system design should ideally be uncoupled, so that each area knows its exact mission and can pursue its objectives. If the FR's are coupled, so that the same DP's are being used to achieve the same set of goals, it is hard to identify the contribution of one part of the system to the result. This can lead to confusion, inefficiency, "turf fights" between different areas, and require micromanagement to operate the system successfully.
4.2 Analysis of Measurables Design

4.2.1 Using Axiomatic Design for the FPS Design Problem

The concepts of axiomatic design can be applied to show how well the FPS measurables work to meet Ford's objectives for lean production. This section will examine how the customer wants (*i.e.*, quality, cost, timing, etc.) are translated to functional requirements, and how design parameters can be developed to meet these requirements. An analysis is done first on the general case of lean production system design, based on eliminating the seven wastes as used in the Toyota Production System [22], and then on the design of the main elements of the Ford Production System.

The analysis uses the four domain concept of axiomatic design to outline how a production system can meet the design goals of lean production. Measurables can be developed which support the domains. The diagram in Figure 4-3 illustrates how measurables can be designed to measure performance of the designed manufacturing system at three different levels.
4.2.2 Control Hierarchy

The control decisions used to run a plant can be decomposed into a hierarchy of different decision-making levels. The concept is that each level has a different relation to actions on the plant floor and needs the appropriate set of metrics to control the manufacturing system. The measurables in the different levels supporting the four design domains, as shown in Figure 4-3, do not necessarily correspond exactly to the appropriate measures for each level of control. In general, however, the relevant measures in the control levels should be those which can be impacted by decisions at those levels.

Thor describes a hierarchical system where each level receives the measurement feedback needed for that level of control [33]. This can be adapted into a model that uses three levels:

<table>
<thead>
<tr>
<th>Level</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level I</td>
<td>Manufacturing Process Level</td>
<td>Control and improvement decisions made on the plant floor.</td>
</tr>
<tr>
<td>Level II</td>
<td>Analysis Level</td>
<td>Measurement of the achievement of business goals, where decisions are made by engineering, maintenance, or middle management.</td>
</tr>
<tr>
<td>Level III</td>
<td>Production System Design Level</td>
<td>High-level management makes decisions regarding the structure or design of all elements and changes in resources.</td>
</tr>
</tbody>
</table>

Figure 4-4 describes the information flow between the plant operations and the different levels of control. The arrows indicate the feedback of measurables information from the plant to the different groups and the actions or decisions taken. The concept behind this diagram is that the feedback loop and inherent time delay between receiving information and implementation of decisions is much greater in Levels II and III than at the Level I operator level. This idea must be considered when the manufacturing system and measurables designs are being developed.
4.2.3 Analysis of Lean Production Design

A good example illustrating the application of axiomatic design to the design of production systems is Toyota, well-documented for the success of their lean production system. Toyota considers seven different forms of *muda*, or waste, as described in Table 4-1. The key principles of the Toyota production system are to maintain the best quality, lowest cost, and shortest lead time, and this is done through the elimination of all of these forms of waste wherever they exist in a manufacturing system.
Table 4-1  The Seven Cardinal Wastes of Toyota

<table>
<thead>
<tr>
<th>Waste</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overproducing</td>
<td>Producing more product than demanded. This is the worst of the 7 wastes - overproduction hides all the other wastes.</td>
</tr>
<tr>
<td>Waiting</td>
<td>People and equipment waiting due to lack of supplies, information, or synchronization of work.</td>
</tr>
<tr>
<td>Transporting</td>
<td>Transportation which does not add value, including the use of warehousing steps in the process.</td>
</tr>
<tr>
<td>Processing</td>
<td>Producing the wrong product, or performing operations not required by the customer.</td>
</tr>
<tr>
<td>Unnecessary Inventory</td>
<td>Excess raw material, work-in-process or finished goods inventory.</td>
</tr>
<tr>
<td>Unnecessary Motion</td>
<td>Operations which do not add value to the product.</td>
</tr>
<tr>
<td>Producing Defects</td>
<td>Producing defective products, including scrap and repairs. Inspection for defects should be replaced by prevention.</td>
</tr>
</tbody>
</table>

A design solution for a manufacturing system can be developed based on a customer want of reducing costs by eliminating the seven wastes. The design described in Table 4-2 is one example, based on the key elements of Toyota's system. Some of the elements of this table have been developed by Cochran [3].

The Functional Requirements (FR's) can be developed from the seven wastes. For example, to eliminate the waste of overproduction, the FR's are to produce the exact quantity demanded by the customer at the time demanded. The method to eliminate the waste of waiting can be described as both maximizing worker utility, where utility is defined as the percent of useful worker effort [22], and maximizing equipment availability. The other FR's follow the seven wastes closely. Note that there does not need to be a one-to-one relationship between the customer wants and FR's.

Design Parameters are then developed to satisfy the FR's. These represent the elements through which the production system achieves its goals. The Process Variables can be thought of as the actions or decisions required to operate the designed system.
<table>
<thead>
<tr>
<th>Customer Wants</th>
<th>Functional Requirements</th>
<th>Design Parameters</th>
<th>Process Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eliminate the seven wastes</td>
<td>Produce the quantity demanded by the customer (FR1)</td>
<td>Autonomation (DP1) - Machine stops when the right quantity is produced</td>
<td>scheduled quantity to produce</td>
</tr>
<tr>
<td></td>
<td>Produce at the time demanded by the customer (FR2)</td>
<td>Replace the part removed by the next process (DP2) - Lead time reduction methods (DP7) - lot size reduction - waiting time reduction</td>
<td>signal to produce part (i.e., kanban card)</td>
</tr>
<tr>
<td></td>
<td>Maximize Worker Utility (FR3)</td>
<td>Standardized work methods (DP3) - line balancing - standardized operations - multi-functional workers</td>
<td>number of workers - operator skills - assignment flexibility - number of machines a worker handles</td>
</tr>
<tr>
<td></td>
<td>Maximize Equipment Availability (FR4)</td>
<td>Machine Reliability methods (DP4)</td>
<td>TPM activities</td>
</tr>
<tr>
<td></td>
<td>Minimize amount of transportation (FR5)</td>
<td>Plant layout improvement (DP5) - manufacturing cells - conveyance time reduction - manual operations separated from machines</td>
<td>reduce distance a part travels - reduce conveyance distance - decoupled processes</td>
</tr>
<tr>
<td></td>
<td>Produce the Right Product (FR6)</td>
<td>Produce part demanded by the customer or the next process (DP6)</td>
<td>process set-up time</td>
</tr>
<tr>
<td></td>
<td>Reduce Inventory (FR7)</td>
<td>Lead time reduction methods (DP7) - lot size reduction - waiting time reduction</td>
<td>batch size - WIP quantity</td>
</tr>
<tr>
<td></td>
<td>Eliminate Non-value-added operations (FR8)</td>
<td>Kaizen - continuous improvement (DP8)</td>
<td>employee suggestions</td>
</tr>
<tr>
<td></td>
<td>Prevent Defects (FR9)</td>
<td>Autonomation - Machine stops automatically on defect (DP9)</td>
<td>Pokayoke Methods (mistake-proofing)</td>
</tr>
</tbody>
</table>

A design matrix can be developed based on the FR's and DP's of Table 4-2. Equation 5 shows the relationship between the nine FR's and DP's. Note that, except for DP7, each design parameter affects exactly one FR. DP7 affects both FR2 and FR7, although FR2 is only affected indirectly. The diagonal shape of the matrix indicates that this is a decoupled design. The FR's are not completely independent, but the requirements can still be satisfied.

The coupling between FR2: Produce at the Time Demanded by the Customer and FR7: Reduce Inventory takes place because the use of methods to reduce lead time affects both FR’s. The reduction of inventory requires tight control over lot sizes and WIP quantity to be able to deliver parts on-time to the customer.
\[
\begin{align*}
\text{FR1} & : \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \\
\text{FR2} & : \begin{bmatrix} 0 & X & 0 & 0 & 0 & 0 \end{bmatrix} \quad \text{DP1} \\
\text{FR3} & : \begin{bmatrix} 0 & 0 & X & 0 & 0 & 0 \end{bmatrix} \quad \text{DP2} \\
\text{FR4} & : \begin{bmatrix} 0 & 0 & 0 & X & 0 & 0 \end{bmatrix} \quad \text{DP3} \\
\text{FR5} & = \begin{bmatrix} 0 & 0 & 0 & 0 & X & 0 & 0 \end{bmatrix} \quad \text{DP4} \\
\text{FR6} & : \begin{bmatrix} 0 & 0 & 0 & 0 & X & 0 \end{bmatrix} \quad \text{DP5} \\
\text{FR7} & : \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \quad \text{DP6} \\
\text{FR8} & : \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \text{DP7} \\
\text{FR9} & : \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \quad \text{DP8} \\
\end{align*}
\]

Equation 5  Lean Production System Design Equation

The axiomatic design methodology allows one to clearly show the relationships between DP's and FR's, and between PV's and DP's. A theorem based on the two axioms states that in an ideal design, the number of DP's equals the number of FR's. When the number of DP's is less than the number of FR's, either the design is coupled, or the Functional Requirements can never be satisfied. Similarly, when there are more DP's than FR's, either the design is redundant or it is coupled. The design based on the seven wastes has the same number cf DP's as FR's.

From the design outlined in Table 4-2, a set of metrics can be developed to track progress in fulfilling the FR's, DP's, or for control of the process. The diagram in Figure 4-5 indicates that measurements can be developed for each level of the control hierarchy. Table 4-3 lists some measures based on the lean production design. In general, these measures are defined to support the decisions made at the different control levels, Level I to Level III.
In some cases, the measurables at Level I will be the same as the control or process variable. For example, the process variable to control lot size reduction is production batch size, which is also the measurable at this level. In other cases, the measurables are derived from the process variable. Pokayoke methods are the actions performed to implement automation (DP9). The measurable derived to measure this for Level I of the hierarchy is the number of defects.

Table 4-3 Measures to Support the Different Design Domains

<table>
<thead>
<tr>
<th>Customer Wants</th>
<th>Functional Requirements (Level III)</th>
<th>Design Parameters (Level II)</th>
<th>Process Variables (Level I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Volume Performance</td>
<td>Number of Operations</td>
<td>Number of Operations</td>
<td>Length of Part Travel</td>
</tr>
<tr>
<td>On-Time Delivery Performance</td>
<td>Operator Skill Evaluation</td>
<td>Operator Skill Evaluation</td>
<td>Number of Suggestions</td>
</tr>
<tr>
<td>Labor Productivity: time per unit</td>
<td>Number of Manufacturing Cells</td>
<td>Number of Manufacturing Cells</td>
<td>Training Hours of Employees</td>
</tr>
<tr>
<td>Manufacturing Cycle Time (MCT)</td>
<td>Percent of Employees in Teams</td>
<td>Percent of Employees in Teams</td>
<td>Absenteeism</td>
</tr>
<tr>
<td>Percent Value-Added</td>
<td>Number of Job Classifications</td>
<td>Number of Job Classifications</td>
<td>Average Set-up Time</td>
</tr>
<tr>
<td>Number of Defects</td>
<td>Number of Pokayoke devices</td>
<td>Number of Pokayoke devices</td>
<td>Average Batch Size</td>
</tr>
<tr>
<td>Total Cost</td>
<td>Overall Equipment Effectiveness</td>
<td>Overall Equipment Effectiveness</td>
<td>Size of Repair Area (sq. ft.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unplanned Downtime (hours)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean Time Before Failure (MTBF)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Build to Schedule</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Amount of WIP at each process</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Number of Defects</td>
</tr>
</tbody>
</table>

Because the DP’s and PV’s are developed based on the Functional Requirements, the measures will necessarily be related between these three different categories. Thus, in some cases, the measures will be similar at all three levels, exhibiting differences only in the level of aggregation.
For example, for FR7: Reduce Inventory, the measure at the highest level would track overall Manufacturing Cycle Time or Dock-to-Dock Time. At the analysis and manufacturing process levels, Level I and II, the measure should track progress in the DP that relates to this FR, or the reduction of lead time through lot sizes and the amount of WIP at each process. It is useful for the top management level to have information on the plant’s overall ability to reduce inventory or MCT, while at the process level, it is important to measure the trend towards smaller lot sizes over time, which can be directly impacted by the operators.

4.2.4 Analysis of FPS Design

A similar approach can be used for an analysis of Ford's production system design. Table 4-4 uses the principles and stated objectives of FPS from Chapter 2 to develop functional requirements and design parameters for the FPS design. The design parameters are derived from the planned elements of the Plant Operating System.
Table 4-4  Design Analysis of the FPS Design

<table>
<thead>
<tr>
<th>Customer Wants</th>
<th>Functional Requirements</th>
<th>Design Parameters (FPS Programs)</th>
<th>Process Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality</td>
<td>• Improve customer quality</td>
<td>• Produce high quality parts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Reduc costs</td>
<td>• 33% more throughput from existing capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Fully utilize capacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timing</td>
<td>• Reduce time in the system</td>
<td>• Sequenced production</td>
<td>• In-Line Vehicle Sequencing (ILVS)</td>
</tr>
<tr>
<td></td>
<td>• &quot;1-day Mfg. Cycle Time&quot;</td>
<td>• Synchronous material flow</td>
<td>• Order to Delivery process</td>
</tr>
<tr>
<td></td>
<td>• &quot;15-day Order to Delivery&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demand</td>
<td>• Meet customer demand</td>
<td>• Match capacity to forecast</td>
<td>• Capacity planning</td>
</tr>
<tr>
<td></td>
<td>• Fast process launches</td>
<td>• Reduce part complexity</td>
<td>• Part commonality</td>
</tr>
<tr>
<td>People</td>
<td>• Effective workgroups</td>
<td>• Develop employee skills</td>
<td>• Cross-functional workgroups</td>
</tr>
<tr>
<td></td>
<td>• Obtain &quot;employee ownership&quot;</td>
<td></td>
<td>• Training</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Demonstrate management commitment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Improve communication</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Joint Ford/UAW programs</td>
</tr>
</tbody>
</table>

Note that the Ford design is incomplete. The FR's are not well-defined, and do not closely relate to the customer wants, as interpreted from the vision, principles, and stretch objectives of FPS. The DP's chosen to satisfy the Functional Requirements do not exhibit a one-to-one relationship with the FR's. Also, the PV's, or the actions required to operate FPS, have not been fully defined.

The FPS design described in Table 4-4 does not have the clear structure that is observable in the lean production design in Table 4-2. Without the ability to match Design Parameters to Functional Requirements at this highest level of the design, it is difficult to develop the details of the FPS programs and be able to satisfy Ford's objectives without causing program conflicts and confusion.

Measures can be developed to support the implementation of the FPS programs, for the different levels of control in the organization. The list in Table 4-5 describes how the FPS measures match the information required to measure how well the customer wants and functional requirements are satisfied.

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Note that some of the functional requirements such as reducing part complexity are not well satisfied by the set of manufacturing measurables, and may need to be addressed by other components of Ford 2000 such as the Ford Product Development System. Matching capacity to forecasted demand, for example, is not satisfied by the OEE measure, which looks only at the plant constraint operation and does not relate to customer demand in the future. In addition, forecasts are usually in error, so the ability to change production to meet uncertain future demands should be considered.

<table>
<thead>
<tr>
<th>Customer Wants</th>
<th>Functional Requirements (Level III)</th>
<th>Measures</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produce high quality parts</td>
<td>First Time Through</td>
<td>FTT measures in-process quality only, not customer quality</td>
<td></td>
</tr>
<tr>
<td>33% more throughput from existing capacity</td>
<td>OEE</td>
<td>OEE is not an effective measure of the throughput of a plant</td>
<td></td>
</tr>
<tr>
<td>Sequenced production</td>
<td>Build to Schedule</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduced time in the system</td>
<td>Dock-to-Dock Time</td>
<td>Not a direct measure of synchronous material flow</td>
<td></td>
</tr>
<tr>
<td>Match capacity to forecast</td>
<td>(?)</td>
<td>OEE is not useful as a measure of overall plant capacity</td>
<td></td>
</tr>
<tr>
<td>Reduce part complexity</td>
<td>(?)</td>
<td>from another part of Ford 2000</td>
<td></td>
</tr>
<tr>
<td>Develop employee skills</td>
<td>(?)</td>
<td>from another part of Ford 2000</td>
<td></td>
</tr>
<tr>
<td>Obtain &quot;employee ownership&quot;</td>
<td>Employee Surveys</td>
<td>still undefined</td>
<td></td>
</tr>
<tr>
<td>Reduce costs</td>
<td>Total Cost</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.2.5 Design Issues and Measurables Coupling

The axiomatic design methodology can be used to evaluate the details of the FPS design as it is created. For the design of measures, the process can show you if the information used to control FPS is coupled. One example is an evaluation of the OEE measurable as follows:
Overall Equipment Effectiveness measures three main components:

- losses of availability due to equipment breakdowns, setups, adjustments, tooling losses, and startup losses
- losses of performance efficiency due to reduced speed or idling
- quality losses due to rejected or reworked parts

OEE is a composite measure of these components. If the FR's are as follows,

\[
\text{FR1} = \text{Maximize Machine Uptime} \\
\text{FR2} = \text{Minimize Setup Time} \\
\text{FR3} = \text{Minimize Production Defects}
\]

then the OEE measure can be considered to be the one design parameter,

\[
\text{DP1} = \text{OEE Measure}
\]

In this case, the one DP attempts to satisfy the measurement requirement for three FR's, so the design is coupled. The one OEE number cannot provide enough information to monitor or control the three different functions. In a similar manner, losses such as set-up times, downtime due to breakdowns and start-up losses are grouped into one availability measure. A better design would measure these elements separately, measuring set-up time and unplanned downtime, for example.

The problem is not just a difference in how the information is aggregated, but that one measure is being used as information to control a number of different elements in the process. The result is that changes in OEE cannot be directly related to actions by the operator, and more adjustments to the process are required to move the system in the desired direction. This iterative process adds delay in the system which further confounds the results.

**4.3 Summary of Results**

The axiomatic design methodology described is useful as a framework for evaluating production system and measurables design. Although a detailed analysis of Ford’s production system
design was not completed, the work done suggests that this framework is an effective tool for developing a complete system design. The analysis yields the following major results:

Matching the design to the organization's goals
In the outline of Ford's production system design from Table 4-4 and the measures listed in Table 4-5, it appears that this design of FPS is not carefully matched to the main goals or customer wants. The Functional Requirements are not defined explicitly to correspond to customer needs.

The FPS approach to quality does not match the principle of improving customer quality:
- The FTT describes in-process quality only, and not customer quality. Quality should include both the defects seen at the next process and by the final customer.
- The functional requirement does not focus on the prevention of defects, as in the lean production design based on the seven wastes.
- The program designed to address the FR of high quality is the Quality Operating System, a separate program under FPS.

Other goals are not accounted for by the FPS programs or measures:
- Fast process launches are required to meet the stretch objective of a "24-month car," but the production system has not been designed to directly measure or implement this goal.
- Matching capacity to forecasted demand
- Developing employee skills

Information is required to monitor progress in all FR's
The second design axiom can be stated as "to minimize the information content." A robust design is considered to be an uncoupled design with the lowest information required to satisfy the Functional Requirements. As discussed in Chapter 3, one of Ford's goals was to use only a small set of FPS manufacturing measures. In reality, however, there is no one "magic number" one can use to monitor an entire plant. A problem with the FPS design is that, in trying to reduce the amount of information reported and used for control, it has ended up with ratios or composite measures which couple the different elements of the system.
The alternative is a larger set of simple measures, as described in the lean production example in Table 4-3. In this case, the measures are clear, reducing any confusion in their importance, and can be individually impacted, uncoupling the different parts of the system. A large number of measures is not a problem as long as they are independent, or monitor the progress of independent FR's and DP's.

*Measures for all levels in the organization*

The FPS design is missing measures at all control levels. Comparing the FPS measures to the many measures used at different levels in the lean production system design, it is clear that the FPS measures cannot be useful to track improvements in satisfying all of the FR's, DP's and PV's. The FPS measurables appear to be designed for supporting decision-making at Level III, the production system design level, instead of a main focus on continuous improvement or empowering workgroups at Level I. For example, for both FTT and OEE it is difficult to tie actions to results in the overall measure. As discussed earlier, the OEE measurable couples the different elements of the design, making it difficult to use as control information for any of the levels of decision-making. The axiomatic design methodology illustrates the difficulty of using one small set of measures for all control levels of the organization.

### 4.3.1 Recommendations

The details of the FPS design, including the decomposition of functional requirements, design parameters, and process variables, have not been completely developed. From the current plan, the design is not carefully structured. For example, some of the DP's and PV's are described in detail, without the rest of the model complete. The reason for this is that these elements are already in place at some plants in the company.

The difficulty in addressing existing plant production methods illustrates Ford's problem, in trying to change the entire corporate production system at once. This analysis points out that many of Ford's goals have not been met by the current measurables design.

The lean production system design case describes an alternative design that can be used as an example. A recommendation is that Ford rethink the way measures are designed to meet the
company's needs. The measurables and FPS program development need to be developed concurrently. This chapter has provided an approach for establishing this process.
5. Measurables - Use in Management

5.1 Survey Overview

5.1.1 Objectives of Survey

A short survey was developed to obtain feedback from Ford's manufacturing sites on the current use of manufacturing measurables at the plants. The objective of this survey was to examine the measurement practices at different Ford locations, in Europe and North America, and across all of the company's divisions. The survey was targeted at all of the manufacturing plants where the Ford Production System Manufacturing Measurables were launched in the fall of 1995.

The different plant divisions include Vehicle Operations, Powertrain Operations, Automotive Component Division, and Electrical and Fuel Handling Division. These divisions produce substantially different products and use different manufacturing processes. For example, the final assembly of an automobile differs greatly from circuit board assembly in the Electronics Organization of the Automotive Component Division. Therefore, one goal was to compare the measures used for different manufacturing process designs.

5.1.2 Description of Questions, Audience, and Distribution Methods

A copy of the measurables survey is included in Appendix I. It has four main components:

- A list of generic measurables is given following the general categories of Table 5 in Chapter 3. The participants were asked to rate on a scale of 1 to 7 the amount and quality of the data for each of these measures that is used at the participant's management level. The survey also asks for the typical frequency of reporting for each measure, from daily through annual reporting.

- For the same set of generic measurement categories, the participants were asked to choose the measures which they find the most and least useful, as well as to indicate which measures are used for continuous improvement purposes versus for reporting.
The survey also asks which measures are used to evaluate the participants subordinates, or used in their own evaluation.

- The survey asks which measures the participant spends the most time on, and for which areas the participant believes more information is required.
- The participant is also asked to rank by importance a set of general measurement functions.

The target audience of the measurables survey were plant users who were familiar with all of the existing measures used by the plant. Because of the difficulty in finding and targeting individuals at the large number of sites involved, the audience used were the measurables coordinators for each plant chosen to be trained in the FPS measures. Because they were chosen for this responsibility, they were assumed to have good knowledge of the existing practices at their plants, and their contact with the FPS team allowed access for distribution of the survey. These measurables coordinators are generally engineers or low-level managers, although some divisions have assigned representatives from the plant Controller's office, for example.

An initial pilot survey was done with managers of the Ford Production System. The form was revised based on their feedback, and the final version distributed following the FPS measurables training sessions in November and December of 1995. The survey was distributed both manually, at the conclusion of one of the scheduled training sessions, and by electronic mail to all of the FPS measurables contacts at Ford plants in North America and Europe.

5.1.3 Overview of Results

The response rate to the measurables survey was fairly low. From over 150 manufacturing sites involved in the launch of FPS measures, only 25 surveys were returned. Table 5-1 indicates the distribution of these responses by geographical location and by division. The low response rate may be due to the use of electronic mail for delivery, which is not a typical distribution method for this type of material at the company, or the individuals targeted may not always have had knowledge of the measurables use throughout their plant. The small number of returns does not allow for a good statistical analysis of the use of measurables at different locations. However, we can still examine the ratings and general comments from the surveys that were returned.
Table 5-1  Distribution of Survey Responses

<table>
<thead>
<tr>
<th>Location</th>
<th>Division</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>ACD</td>
</tr>
<tr>
<td>Europe</td>
<td>PTO</td>
</tr>
<tr>
<td>Total</td>
<td>VO</td>
</tr>
<tr>
<td></td>
<td>(other)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
</tr>
</tbody>
</table>

Total Survey Responses = 25

Table 5-2 summarizes the results from the first section of the survey, where the amount and quality of current metrics are rated. These ratings are very similar: production volume and quality measures are highly rated, along with meeting budget and overhead expenses. The least used measures appear to be setup times and process flexibility, as well as cross-training of employees and employee satisfaction.

The ratings for reporting frequency parallel the ratings for amount and quality of information. The most frequently reported information by far were production volume and quality numbers, with employee cross-training and satisfaction generally only reported annually, if at all.
The second section of the survey asks the participant to choose the measurement categories which provide the most and least useful information. The results of these responses match those from the category ratings: quality and production volumes, along with labor efficiency, production costs, and meeting budget are deemed most useful. Process flexibility measures, and cross-training and satisfaction of employees are believed to be the least useful.

For continuous improvement activities, the survey participants rated quality, equipment uptime and machine efficiency the highest. There was no consensus on the measures which are used mainly for reporting purposes. The measures used to evaluate subordinates were essentially the same as those used by the participant's boss to judge his performance. Quality is most often used, with production volumes and meeting budget also important.

The survey also asked for where the participant believed that more information was needed. Production costs and preventative maintenance measures were rated the highest here. As for the measures that they currently spent the most time on, quality was rated very high, followed by production volumes and costs, machine uptime, and meeting budget.

<table>
<thead>
<tr>
<th>Amount of Information</th>
<th>Quality of Information</th>
<th>Reporting Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest Rated</td>
<td>Highest Rated</td>
<td>Most Frequent</td>
</tr>
<tr>
<td>Production Volume</td>
<td>Production Volume</td>
<td>Production Volumes</td>
</tr>
<tr>
<td>Quality</td>
<td>Meeting Budget</td>
<td>Quality</td>
</tr>
<tr>
<td>Labor Efficiency</td>
<td>Overhead Expenses</td>
<td></td>
</tr>
<tr>
<td>Meeting Budget</td>
<td>Quality</td>
<td></td>
</tr>
<tr>
<td>Overhead Expenses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lowest Rated</td>
<td>Lowest Rated</td>
<td>Least Frequent</td>
</tr>
<tr>
<td>Process Flexibility</td>
<td>Setup Times</td>
<td>Crosstraining of Employees</td>
</tr>
<tr>
<td>Setup Times</td>
<td>Process Flexibility</td>
<td>Employee Satisfaction</td>
</tr>
<tr>
<td></td>
<td>Crosstraining of Employees</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Employee Satisfaction</td>
<td></td>
</tr>
</tbody>
</table>
Table 5-3  Ranking of General Measurables Functions

<table>
<thead>
<tr>
<th>Rank</th>
<th>Measurables Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Operations Control and Improvement</td>
</tr>
<tr>
<td>2</td>
<td>Performance Measurement and Evaluation</td>
</tr>
<tr>
<td>3</td>
<td>Communication to all Levels of the Organization</td>
</tr>
<tr>
<td>4</td>
<td>Influencing Behavior</td>
</tr>
<tr>
<td>5</td>
<td>Product Costing &amp; Product Line Decisions</td>
</tr>
<tr>
<td>6</td>
<td>Project Evaluation</td>
</tr>
<tr>
<td>7</td>
<td>External Reporting</td>
</tr>
<tr>
<td>8</td>
<td>Influencing the Worldview of the Organization</td>
</tr>
</tbody>
</table>

At the end of the survey, the participant is asked to rank a set of eight general functions of measurables in his organization. The results are given in Table 5-3. The concept behind Ford's design of measurables to meet the most important set of these functions is discussed in the next section.

5.1.4 Analysis of Results

From the summary above, there seems to be a consistent focus on the measures that management believes are important. Quality and production volumes are the metrics that the plant spends the most time on. These are also deemed to be the most useful metrics, and the amount of quality of information gathered is high for these measures.

There appears to be little emphasis on such measures as inventory levels, setup times, and process flexibility. There is also not a strong focus on people measures such as employee satisfaction, employee suggestions, and cross-training. These categories will play a greater role in the implementation of the Ford Production System, and it appears that it is necessary to develop new measures in these areas to be able to implement change. It is also possible that there is more emphasis placed on short-term measures that can be affected quickly by management actions.

The survey participants have expressed the need for additional information in two main categories: total cost and preventative maintenance. The total cost information is wanted to be able to determine how plant decisions and actions affect production costs. Preventative
maintenance information is desired to help in the continuous improvement of machine uptime and machine efficiency.

We do not have enough data to compare plants from different divisions and draw any strong conclusions. An original goal of the survey was also to compare how different levels of management view the measurement process. Because of the difficulty in obtaining data from multiple levels across a number of plants, and the limited number of survey responses, this was not accomplished.

5.2 Measurables as a means to change the organization

5.2.1 Evaluation of FPS Measures meeting a Set of Necessary Functions

A framework one can use to evaluate the choice of measurables for the Ford Production System is to look at how these measures meet the multiple objectives Ford has for FPS. This framework examines how the company intends to change the organization and the role measurables play in this.

The following list proposes one set of functions to use in evaluating the FPS measures:

1. External Reporting
2. Operations Control and Improvement
3. Performance Measurement and Evaluation
4. Communication
5. Project Evaluation and Capital Budgeting
6. Product Costing and Product Line Decisions
7. Influencing Behavior
8. Influencing the Worldview of the Organization

The rest of this chapter discusses some of these functions and how the FPS measures support them.
5.2.2 Use at different levels of management

The FPS measures were launched at the beginning of 1996, and will be first used for reporting by plant management in July 1996. A goal of FPS is to have these measures used by all levels of plant management.

As described in Chapter 4, the different levels of management can be grouped into three main levels:

I. Manufacturing Process Level
II. Analysis Level
III. Production System Design Level

Measurables for Level I are used for control of operations and processes on the plant floor by operators. The next level uses measures for analysis by engineering and middle-management. At the production system design level, the measures indicate if the reengineering activities such as the Plant Operating System processes are working as planned or are other actions required.

As discussed earlier, this characteristic of a common set of measures was expressed as an early design goal, although it is not clear that this benefits the use of these measures for FPS. In fact, many managers have expressed concern about how useful these measures are at the different levels. One manager expressed the idea of using process measures such as OEE to evaluate the production system design as being akin to “using a speedometer to judge the end of the trip.” In other words, OEE may be useful at the process level to gauge the effect of process improvements, but the OEE number will not inform upper-management of overall improvement in plant output. In a similar light, certain measures may provide a good assessment of how well the overall plant process is doing, but be less useful for individual operators in making decisions. Dock-to-Dock time and inventory measures, for example, may be more useful as aggregate numbers than for individual areas.

Part of the concerns lie in the difference in timeliness required for using measures appropriately at different levels. The closer you get to the manufacturing process, the more rapid the feedback should be. The initial reporting process involves collecting plant data and reporting monthly. This creates an upward focus of communication, where time is spent on gathering data for
reporting "how well things did" instead of "where are we now and what changes can we make to our direction." From the measurables training, the plan is to have plant floor operators collect much of the data daily for use in controlling the manufacturing process and not just for reporting. The FPS team has been conservative in predicting how soon this will happen, and one manager has predicted 3-5 years before operators on the floor are using the measurables information in this manner.

Other concerns are with the method of calculating plant-wide measures, for example. The plant-wide numbers will be calculated using control parts and cost-weighted averages of individual processes. The control parts will cause concern because no matter how well they're chosen, they may not adequately indicate how well the plant as a whole is performing, and can lead management to focus on the wrong problem.

In addition, the new FPS measures will be used alongside existing measures at each of these levels. Plant management is not sure if the new measures will tell them useful information, so they will keep the FPS measures separate until they are proven out. This was expressed as a major concern at the pilot training session for the FPS measurables, where both plant management and floor workers believed people would be reluctant to track several new measures on top of the ones they were currently monitoring.

A later section of the chapter includes a rating matrix where the use of each of the four main FPS measures at these three different levels of control is discussed further.

5.2.3 Evaluation of Plant Management

Evaluation of performance is a key function of measurables, and Ford intends to use the FPS measures as a primary means of evaluation for plant management. The first six months of 1996 will be used to establish a baseline at each plant. After that, the measures will be part of management’s performance reviews. It is unclear at this point how this will happen exactly. There may be pre-determined targets, or management may be measured by the percentage improvement in certain measures.

This new system of evaluation will influence what plant managers will focus their attention on. In the past, you could describe plant management as being rewarded for being entrepreneurial
and aggressive. As one manager described, "Now you're telling them to be conformists." This requires a change in the reward systems, which do not reward teamwork and commonality right now.

The new FPS measures intend to change the focus of plant evaluation from financial to physical measures. Although the goal is to reduce the emphasis on typical financial numbers such as labor and overhead expenses, these numbers will still be collected. It is not clear how the company will resolve conflicts between the goals of reducing Dock-to-Dock Time and improving OEE and the objective of minimizing direct and indirect labor expenses. The Total Cost measure which is intended to address part of this issue has not been fully developed. Even so, there is a question of how priorities will be set when making tradeoffs between the different measures.

5.2.4 Influencing Behavior

An important function of the FPS measures is to alter the current behavior of plant management, to align their objectives with the goals of FPS. The FPS management team believes that the measurables drive behavior, force it to become routine, and then become ingrained in people and plant processes. By aligning objectives in different areas of the plant, the measures will also help reduce stress caused by conflict between groups.

FPS represents a culture change that Ford is trying to implement. As one manager described, "You need to enforce [the new production system] from the top-down, not bottom up to change the company." The FPS team believes that the required cultural change needs to be pushed down throughout the company by individual plant managers. This explains why the measures are initially oriented towards reporting and control up to management.

Another issue related to influencing employee behavior is the top-down approach of the measurables development and launch. The launch of the FPS measures is very top-down; the FPS team is telling all plants what to use with no plant level input, although manufacturing representatives were involved at the beginning of the measurables design.

One of the FPS managers described the concept of using the measurables as a "Trojan horse." The production system team is almost "tricking" the plant into using these measures. They begin
taking the required new data because plant management is evaluated on these new numbers. Once the measurement process has begun, the plant will need processes to improve these numbers on the shop floor. Thus, the measures create a need for the introduction of lean production techniques. A function of the measures, then, is to increase the willingness of plant management to adopt the elements of the Plant Operating System as they are launched.

5.2.5 Influencing Worldview

An extension of influencing the behavior of people at the manufacturing sites is how the FPS measures will modify the “world-view” or “big picture,” how employees think of their role in the organization. As one manager discussed, the launch of the measurables is designed to put the organizations into a “readiness state.” The goal is to “break old plant cultures, put pressure on plant managers, and create an environment to look at the business differently.” Two major changes involve the commonization of measures across all plants and management by total cost.

As discussed earlier, the FPS measures will be the first attempts to standardize the things that all manufacturing plants track and report. An obvious benefit of this is to allow for comparison or competition among plants. The FPS team stresses that this is not a goal or a desired outcome, and that comparisons will not be done because all plants have different processes. In practice, it will be likely that comparisons will be performed, and one advantage is in allowing best practices to be discovered and adopted throughout the company faster.

Another change in employee mindset is management by total cost versus such traditional financial measurements as labor and overhead expenses and comparison to budgeted values. The total cost measure has the potential to provide the most sweeping changes of any of the FPS measures as it can be used to share information for decision-making between different parts of the organization such as production and product development, with the overall goal of meeting the stretch objective of cost reduction.

The FPS management wants to use information as a competitive advantage. As one manager expressed, you can look at the use of plant floor information as having three modes: React and Report, Information Storage, and Knowledge-Based. Most Ford plants are in the first mode of reporting data without using much of the data to control the process. A few plants are in the second phase where information is compiled and used for analysis and problem-solving. No
plants are really in the knowledge-based stage, where processes can capture the knowledge and experience of workers and apply this for design.

5.2.6 Measures for Plants with Different Processes

Ford is deploying the FPS measures at all plants in the company. Most of the FPS and plant management are convinced that this is a good idea, to standardize measures and the rules for calculating and comparing them, preventing the confusion that currently exists between measurement systems of different plants and divisions.

Another problem is that the plants have a tendency to measure everything they value as important, making it hard to decide where to focus efforts on the floor. The FPS measures may help in setting priorities, assuming that the chosen measures are aligned with the direction Ford wants to go for Ford 2000.

Plant management does seem to agree that Ford needs to allow some variation or adaptation by the plant beyond these standardized corporate measurables. One reason for this is the need to support temporary objectives, such as for meeting programs such as ISO9000 or the launch of new products. Management often uses situational measurables to support these special functions.

Another purpose for different measurables is that the processes vary widely between plants and divisions. Ford's plants produce such diverse products as glass, engine components, interior and exterior trim, circuit boards, transmissions, engines, and vehicle assemblies. Though the same FPS measures can be applied to all of these different processes, there are different priorities for each process, and additional measures may be required, such as the following:

- Components plants require a different approach to Build to Schedule than Vehicle Assembly plants, for example. In some cases, the exact build sequence of parts may be very important, while in others the measurement adds little value and can impede production.
- Some plants produce product lines with many models, which may require more careful delivery and more attention to the Build to Schedule measure.
- For some products such as electronics, the material costs are a high percentage of the final product cost, and it is important to measure inventory levels well.
• Some plants use dedicated lines or have minimal product variety. Measures of setup times or flexibility are not as critical for these plants.
• Supplier defects are important for complex assemblies, while some products such as plastic moldings have no need for these measures.

The FPS measures were pilot tested at a number of different plants and manufacturing processes to determine if the same measures could be used at all locations. The measures will have to be reevaluated after they have been in place over a longer period to indicate whether the concerns described above can be put to rest.

5.3 Rating Matrix - Strengths and Weaknesses

From the concerns expressed by management through interview, a matrix can be compiled which rates the four key FPS measures for their ability to be used at different levels in the organization: the manufacturing process level (I), analysis level (II), and production system design level (III).

Table 5-4 Rating Matrix of Measurables for Different Levels of Analysis

<table>
<thead>
<tr>
<th>Measurable</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Time Through</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Dock-to-Dock Time</td>
<td>O</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Build to Schedule</td>
<td>-</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Overall Equipment Effectiveness</td>
<td>O</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

The simple matrix in Table 5-4 indicates how well the measures appear to meet the needs expressed by management for these three levels of control. The plus signs indicate that the measures meet the required function especially well, while a minus sign indicates the function is poorly met. An "O" indicates that the measurable is useful, but does not meet all the needs at the control level. Each of the measurables can be discussed individually.
**First Time Through**

The FTT measures overall process quality, and does capture the main sources of in-house quality. A benefit of this measure versus current practices is that quality issues such as retests and reruns are still recorded. Some managers have expressed the concern that FTT looks only at the existing process, and not product quality or quality to the customer.

For example, FTT does not reflect any of the output measures of quality that are important to the customer such as warranty costs or repairs per 1000 vehicles (R/1000). Components plants, for example, also use measures such as number of TNI's (part trouble not identified by the dealer during service). These measures and warranty measures allow product and process problems to be detected and solved. These output measures encourage a different approach than using only a process measure such as FTT. Changing the process to improve FTT may have a negative impact on overall customer quality. The output measures are important to track the effect of such things as component changes or engineering changes. In general, warranty measures should be correlated with FTT, but this may not always be the case.

Some managers believe that "FPS is forgetting about quality," and that quality systems are not as closely integrated with the FPS design as they should be. The lower ratings in all three management levels reflect this concern about the lack of emphasis on quality.

**Dock-to-Dock Time**

Management expressed the least concerns with the Dock-to-Dock measurable. This is generally considered a good measure of inventory and plant-wide "speed," and the measurement of inventory, as evidenced in the results of the measurables survey, currently does not receive sufficient focus. DTD is also considered to have large implications on quality from a production point of view, in terms of reaction time to problems. In addition, the DTD measure may give both manufacturing and material management personnel shared objectives, and may therefore be an improvement over the similar measure, Manufacturing Cycle Time.

For use on the plant floor, however, it will be difficult for individual operators to affect this measure directly, and they may see this number go up and down with no apparent action on their part. The demand for WIP in a particular area depends on the processes which precede and
follow that area, and on the scheduling process, and not only on things that can be controlled in one area.

As described in Chapter 3, management is also concerned that "JIT warehouses" or "special" parts storage areas can be created outside of the normal measured inventories, to serve as buffers for the manufacturing process.

**Build to Schedule**

Most managers agree that the concept of daily schedule attainment is a good one, and believe it focuses the plants to produce only to demand, and not to just "run the plant flat out." A major concern is that not all plants are designed to operate to meet delivery in a particular sequence, and it is not clear that this measure provides any added value to these plants. The BTS measure appears to be driven from the goal of using In-Line Vehicle Sequencing, Ford's process of producing vehicles in the assembly plant in a frozen sequence and driving supplier plants to meet this sequence.

The complications that the sequence term contributes makes the measure less than ideal as a way to track delivery performance. This is especially true when used by operators to control the manufacturing process. At the analysis level and higher, the measure may be useful to track the plant's progress in its capability of volume production and mix flexibility.

**Overall Equipment Effectiveness**

OEE is the most controversial of the FPS measures. The chief concern is that, as a plant-wide number for reporting it does not provide useful information. The OEE measure at the plant level is intended to measure only the constraint or bottleneck operation. Management's concerns are that this constraint will move, and the effect on the OEE measure will cause confusion. A majority believe that OEE is a useful tool at the analysis level, when complementing the FTPM process, but that the numbers are not adequate as a measure of production throughput, machine reliability, or the use of capacity.

The use of the OEE measure at the plant floor level is also of concern, more because the measure is designed for reporting and tracking over long periods rather than daily control of the manufacturing process, for example. OEE is a composite measure which can disguise such
important elements as setup time and machine uptime. Other managers believe that composite measures such as OEE enable you to capture the effect of many different things at once. Looking at these elements separately may not allow you to determine if things are better or worse.
6. Indicating Progress in Ford's Reengineering

6.1 Measures and the Implementation of Lean Production

6.1.1 The "10 steps" model

There has been a lot of work done on the requirements of a "lean" system of manufacturing, as shown in the review of lean production literature in Chapter 2. One concept that can be developed is to look at the sequential and parallel steps that need to take place in the process of implementing lean production.

The sources on the Toyota Production System outline the elements that were critical in developing Toyota's current manufacturing strategy [22]. Black also discusses the important sequential steps of what he calls IMPS or Integrated Manufacturing Production Systems [2]. Using these concepts, this thesis has developed a model which outlines the process Ford must follow to implement lean production, and where the FPS measurables will fit into this process.
Table 6-1  A Description of 10 Steps Required for Lean Production

<table>
<thead>
<tr>
<th>Steps</th>
<th>Desired Traits</th>
<th>Typical Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Machine Layouts</td>
<td>short length of part travel</td>
<td>length of part travel</td>
</tr>
<tr>
<td></td>
<td>reduced number of operations</td>
<td>number of operations</td>
</tr>
<tr>
<td></td>
<td>reduced plant space</td>
<td></td>
</tr>
<tr>
<td>2  Effective Workteams</td>
<td>skilled workforce</td>
<td>skill evaluation</td>
</tr>
<tr>
<td></td>
<td>employee involvement</td>
<td>number of suggestions</td>
</tr>
<tr>
<td></td>
<td>continuous improvement activities</td>
<td>number of job classes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>training hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td>absenteeism</td>
</tr>
<tr>
<td></td>
<td></td>
<td>percent in teams</td>
</tr>
<tr>
<td>3  Standardized Work</td>
<td>streamlined work flow</td>
<td>productivity measures</td>
</tr>
<tr>
<td></td>
<td>optimal workload for each employee</td>
<td></td>
</tr>
<tr>
<td>4  Reduce Set-up Times</td>
<td>short set-up times</td>
<td>changeover time</td>
</tr>
<tr>
<td></td>
<td>small batch sizes / &quot;batch of one&quot;</td>
<td>average batch size</td>
</tr>
<tr>
<td>5  Mistake Proofing &quot;Built-in Quality&quot;</td>
<td>inspection at each station error-proof design of part / fixture</td>
<td>number of defects per unit size of repair area</td>
</tr>
<tr>
<td>6  Reliable Equipment</td>
<td>preventative maintenance to maximize uptime</td>
<td>unplanned downtime MTBF</td>
</tr>
<tr>
<td>7  Level Production,</td>
<td>produce to demand</td>
<td>number of disruptions to schedule</td>
</tr>
<tr>
<td>Sequenced Production</td>
<td>reduce variability in quantity and product mix</td>
<td></td>
</tr>
<tr>
<td>8  Just-in-Time</td>
<td>&quot;pull&quot; system for controlling quantity and timing</td>
<td>build-to-sequence percent on-time delivery</td>
</tr>
<tr>
<td>9  Reduced Inventory</td>
<td>minimum inventory</td>
<td>dock-to-dock time</td>
</tr>
<tr>
<td></td>
<td>delivery right to production line</td>
<td>total inventory</td>
</tr>
<tr>
<td>10 Cost Reduction</td>
<td>elimination of waste focus on non-value-added activities</td>
<td>total cost</td>
</tr>
</tbody>
</table>

The model described in Table 6-1 includes ten main steps for implementing lean production, and is similar to the foundations and concepts of the Toyota Production System discussed in Section 3.4. Some of the desired traits or outcomes from each step are also listed. The typical measures described in the table are not necessarily used by Toyota, but are derived from different sources on lean production systems.

The steps describe what is important for lean production systems to work, and their order is important, although these elements do not necessarily have to be sequential. For example, machine reliability is an early focus of FTPM and FPS. The methodology used to improve machine uptime can be much more effective if effective workteams have been created, and in fact this is a goal of FTPM, to establish small group activities. In addition, standardized work improves equipment reliability by eliminating variability in the way the way equipment is used.
In general, then, the success of the later steps such as Just-in-Time and reduced inventory depend greatly on earlier steps such as machine layouts, reduced set-up times and reliable equipment.

Using the domains of Axiomatic Design from Chapter 4, the ten steps can be described as encapsulating both the Functional Requirements (FR’s) and Design Parameters (DP’s) of lean production. A problem is that they do not explicitly call out the mapping between the FR’s and the Customer Wants or the DP’s and FR’s. This model can be helpful, however, in evaluating how the FPS measures will satisfy the different stages of the FPS implementation process, illustrating where the measurables feedback is useful and where additional information is required.

6.1.2 FPS measurables and the implementation steps

Developing measures which can be used to control and evaluate progress is a critical part of the implementation process of lean production. FPS managers and responses from the Ford plants agree that choosing good manufacturing measures should help in successfully implementing the changes required for FPS. The diagram in Figure 6-1 shows how the FPS measures target the different steps.
There is not always a one-to-one correspondence between the FPS measures and the different steps, but the diagram indicates the major relationships. Each of the steps can be discussed individually.

**Machine Layouts**

The improvement in the use of plant space is one of the most visible characteristics of lean manufacturing. The FPS design does not directly measure the effect of changes in machine layout that complement lean production. As shown in Figure 3 in Chapter 2, the process of designing plant layouts is being addressed by a group outside of FPS. The problem with this approach is that the success of FPS relies on this process as a foundation, so that the work of the plant layout design group is tightly coupled with the manufacturing operations. It is important to use measures which integrate the functions of both these groups.
Effective Workteams

An Employee Survey measure, though not fully defined, will be used by FPS to measure progress in this step. It is important that the measure includes elements that correspond to the training and employee involvement processes that are developed. Thus, measures of skill level should be developed to measure progress in training, and indirect measures such as the number of suggestions submitted and the percentage of employees in teams can help monitor the level of employee involvement.

None of these measures accurately indicate how "effectively" the workteams operate. However, managers have expressed the notion that people issues are critical for getting lean production to work on the plant floor, and the use of a set of simple employee measures will help identify these issues.

Standardized Work

This step involves defining the work sequence for each employee and streamlining the flow of work through continuous improvement and the elimination of waste. The FPS measures do not track these improvements directly. To monitor progress and motivate employees to make improvements, productivity measures such as man-hours per vehicle or total units per employee (direct and indirect labor) can be used. Note that the goal is not to measure the labor efficiency or the number of direct labor hours per unit, but to indicate how improvements have affected overall plant performance. Although the productivity measure is affected by such things as part and process design, trends in the measure can be used for continuous improvement.

Reduce Set-up Times

Machine set-up times are an indicator of process flexibility. Rapid changeovers allow the reduction of batch sizes, allowing both reduced inventory and the ability to meet a level production schedule. They are also not measured by the FPS measurables. The OEE measurable does indicate losses in the machine availability, and set-up time is one of the "six big losses" that Nakajima recommends be monitored for continuous improvement purposes [2]. As a control measure, however, OEE is not useful for focusing on set-up time reduction. Instead, in trying to reduce availability losses, operators may look instead to reduce the number of setups, increasing the batch size, which would be a negative effect.
**Mistake Proofing**

The FPS design uses FTT to control process quality. FTT does capture many of the quality losses associated with a process, including scrap, repairs, retests, etc. First Time Through is not designed to eliminate end-of-line inspection as a means to detect these defects. The concept behind "Built-in Quality" is to design the process so defects are automatically detected or prevented. The mindset is one of prevention versus reaction, and the goal should be zero defects. A typical output measure might be the total number of defects in an assembled product. One measure of the prevention process, for instance, might be the number of pokayoke, or mistake-proofing, devices installed.

**Reliable Equipment**

Lean production methods such as Just-in-Time are less tolerant of machine breakdowns. Because of this, many experts recommend TPM as a cornerstone to the implementation of lean production [25].

OEE will be used as a measure for FPS. OEE may be a good measure for TPM analysis, but as a composite measure may not indicate progress in machine uptime improvements across a plant. As one author recommends, in addition to the OEE number, the calculation of losses - breakdown loss, startup loss, tooling loss, minor stoppages, quality loss, speed loss, etc. - should be tracked. This would negate the advantage of OEE as a single measure and would create confusion. Simpler measures such as the number and duration of breakdowns (Mean Time Before Failure and Mean Time To Repair) or total unplanned downtime may capture this information better. Another case for simpler uptime measures is that a majority of managers interviewed felt that more data collection on machine uptime was required than currently being collected.

**Level Production**

Companies using lean production methods in Japan stabilize the product mix and volume, reducing variability in the product demand. Equipment reliability and quality improve due to this technique, since the manufacturing process works better if run on a smooth basis. The Build to Schedule measurable fulfills some of the needs of this step, by indicating how well the plant is able to meet the mix and volume scheduled in an exact sequence.
Some managers have expressed the idea that the plant does not control level production, which is decided by the order-to-delivery process. However, it is the plant that both enables and benefits from level production. Short set-ups and job rotation, for example, allow the plant to meet a level production schedule, and the production smoothing in turn simplifies the manufacturing process greatly. FPS and the scheduling process are thus closely coupled, and a measure of the plant's ability to meet a level production schedule is important to integrate these functions.

*Just-in-Time*

As set-up times are reduced and equipment made more reliable it becomes possible to use a "pull" system to produce directly to customer order. FPS uses the BTS measure to indicate daily performance to schedule. Other measures which would be useful in monitoring order performance include the percentage of on-time delivery, and the cycle time between the plant and the customer. For example, lean producers often go from "days of float" to "hours of float" between a components plant and an assembly plant, and a measure of float inventory or cycle time would be a useful gauge of the performance of the JIT system.

*Reduced Inventory*

The earlier steps allow the plant to reduce inventory. Ford's Dock-to-Dock Time measure is a good indicator of the inventory in a process, with a focus on improving the "speed," and it is an easy measure to calculate. It is important to note that the ability to reduce DTD comes from such elements as machine layouts, reduced setup times, high product quality and machine reliability, and level production. DTD is therefore an important measure, but is a result of a number of different groups and actions.

*Cost Reduction*

This last step describes the concept of eliminating waste to reduce overall costs. Each of the other steps are an approach to eliminating particular wastes and thus contribute to this cost reduction. Ford plans to use a Total Cost measure to evaluate plant performance, and the other FPS measures are seen as driving the plant towards the reduction of total cost. In this respect, the Total Cost measure is a good summary measure, and measurables such as DTD can be applied to focus on the details of eliminating non value-added activities in the manufacturing
process, for example. As in the case of the Japanese producer described in Section 2.3, one can measure "total costs down" for overall plant success, but the attention should be placed on improving other direct measures [14].

6.2 Interactions between Components of Ford 2000

6.2.1 Measurables and Other Areas of Ford 2000

Measures are considered a foundation of FPS because they are necessary to align the objectives of everyone in the organization. Each of the parts of Ford 2000, such as the Ford Product Development System, Order to Delivery, After Sales Service and Management Systems will develop their own metrics to support their goals. It is not important to use the same metrics in each group, and in many cases this will not make sense if the business needs are different. It is in the interactions between different groups that cross-functional metrics can be the most beneficial, to align the objectives between functions, or at least to reduce conflicts.

Table 6-2 describes some of the concepts that will require interaction between FPS and other parts of Ford 2000. Note that none of the FPS measures perform well as an indicator for these cross-functional processes. Specific measures need to be designed to address this alignment issue.
Table 6-2  Cross-functional Processes Important to FPS

<table>
<thead>
<tr>
<th>Interaction with FPS</th>
<th>Ford 2000 Corporate Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus on Customer at all stages of the process</td>
<td>FPDS  OD  CP  AS</td>
</tr>
<tr>
<td>Capacity planning</td>
<td>X     X     X     X</td>
</tr>
<tr>
<td>Optimization of global operations</td>
<td>X     X     X</td>
</tr>
<tr>
<td>Process and product design</td>
<td>X     X     X</td>
</tr>
<tr>
<td>Machine layout design</td>
<td>X     X</td>
</tr>
<tr>
<td>Total cost over the product life-cycle</td>
<td>X     X</td>
</tr>
<tr>
<td>Knowledge and technology transfer between plants</td>
<td>X     X</td>
</tr>
<tr>
<td>Flexibility for product mix and reusability</td>
<td>X     X     X</td>
</tr>
<tr>
<td>Global supply base</td>
<td>X     X</td>
</tr>
</tbody>
</table>

Note: FPDS is the Ford Product Development System  
      OD is the Order to Delivery System  
      CP is Capacity Planning  
      AS is After Sales Service

An "X" indicates that there is an interaction between FPS and the specified corporate process.
7. Summary/Conclusion

7.1 Summary of Design Analysis

This thesis has used several approaches to evaluate the design of measurables being launched for the Ford Production System. Each of the different approaches provides some insight into how well the measures support Ford's goals of lean production.

Using the axiomatic design methodology, we determined that the FPS measures do not support all of Ford's objectives. There is also no clear connection between the elements of FPS and the measurables. Axiomatic design was used to develop measures to support a lean production system based on eliminating the seven wastes used by Toyota. The FPS measures were compared to these lean production measures, and to the steps required in the implementation of lean production. This analysis indicates that additional measures should be used to track progress in achieving the functional requirements of lean production. The following areas are not supported by the FPS measurables:

- Matching Capacity to Customer Demand
- Fast Process Launches to Support a "24-month Car"
- Reducing Part Complexity
- Employee Skill Development
- Defect Prevention

The results of a survey and management interviews confirm that current measures do not match what is required for lean production. There is a consistent focus on measures such as quality, production volumes, and meeting budget, but little emphasis on some key measures that are important for FPS:

- Inventory and Dock-to-Dock Time
- Set-up Times
- Process Flexibility
- People Measures

The survey responses also indicate the need for better maintenance and machine uptime data. These results agree with Ford's current state analysis, which determined that machine reliability can provide the most return on investment of any of the FPS programs, and FTPM is considered a foundation of FPS for
this reason. These results also support the idea that the OEE measurable currently used has not proven to be suitable for measuring or controlling machine reliability or plant capacity.

7.2 Recommendations

From the summary above, suggestions can be made for the design of measurables at Ford. The recommendations are summarized in three categories:

- Use a structured design process to develop a production system design and measurables design which support Ford's goals.
- Design measures which support Ford's objectives, and can be used to monitor and control the process at all levels of decision-making.
- Manufacturing measures should be integrated with the other processes of Ford 2000.

*Use a Structured Design Process*

Ford needs to clearly state the corporate functions it wants to measure, and design measures to monitor each of the corporate functions independently. Elements of Ford's manufacturing system design such as Level Production and Synchronous Material Flow need to first be fully outlined before measures are designed to support this. The measures to support Ford's system need to be developed for each level of control in a plant, including the manufacturing process level, analysis level, and production system design level. The characteristics used to choose the set of FPS measures were described in terms of being "few in number," "common," or "used by management and the workforce." These characteristics do not relate to the functional requirements, and do not allow the measurables design to adequately support the different goals of FPS, resulting in a poor design. A structured design approach such as the axiomatic design method described would help Ford to develop the appropriate requirements and corresponding measures to meet these goals.
Measures Based on Ford's Objectives

The measurables design process is closely tied to the development of the manufacturing system design. Once Ford develops the detailed steps of lean production that it wishes to follow, it is easy to define measures at the different levels of the manufacturing system which track progress in these steps. The measures required to control a lean production system should address the following:

- Machine Layout Improvements *(i.e., length of part travel, plant floor space)*
- Effectiveness of the Workforce
- Quality - both in-process and customer measures, focused on prevention
- Set-up Times
- Machine Reliability
- Delivery Performance
- Inventory or Dock-to-Dock Time
- Reduced Overall Costs

The measurables do not have to be common for all levels of management. Measurables chosen for each level of control should be ones which can be directly impacted by decisions made at that level. The FPS measures also do not have to be "few in number," as this means that either important information is missing or the measurables design is coupled. The axiomatic design analysis used in this thesis illustrates the coupling created by composite measures such as OEE and Build to Schedule. A larger set of measures will eliminate confusion and uncouple different parts of the manufacturing system.

In addition, a good definition of total cost and how it will be used is important as an overall measure of progress towards lean production. Reducing this number is the basis for trying to eliminate the "seven wastes", to provide more value at a lower cost to the customer.

Manufacturing Measures Should be Integrated

The FPS measures should be integrated with all processes of Ford 2000. An important use of metrics is to influence management behavior and to initiate a change in corporate culture. The Ford Production System is a radical change in the company's operations, and a well-designed set of metrics and incentives which are consistent with the corporate principles helps accomplish this change. Because FPS interacts with all of the other Ford 2000 processes, corporate-wide measures must be designed with all groups of the company in mind. The measures needed for successful operation of FPS may be developed by another design group, for example, but it is still important that the plants take ownership in the result.
The plants will ultimately be affected by such things as capacity planning, machine layouts, employee skill levels, and the speed of process launches.

7.3 Conclusion

"When you can measure what you are speaking about, and express it in numbers, you know something about it ... [otherwise] your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in thought advanced to the stage of science."

- Lord Kelvin

The quote from Lord Kelvin can be applied not just to scientific research, but to organizational structures and manufacturing system design. Just as measures such as machine efficiency and direct labor were critical for the mass production system, certain measures will be critical for running a lean production system.

Ford is undertaking what may be the largest reengineering effort ever. They are committed to changing their production system and believe that new manufacturing measures are an important part of this. In many ways, it makes sense for Ford to use a small set of measures as a foundation for a lean production system, as they change the mindset of plant management and allow the plants to focus on the important elements. Ford needs to create better ties between what it is measuring and the detailed initiatives that they are trying to implement. It will be difficult to create an effective production system unless this is done successfully.
Appendix I  List of Abbreviations

ACD  Automotive Components Division
BTS  Build to Schedule
CIRS Continuous Improvement Recognition System
CW  Customer Wants
DP  Design Parameters
DTD Dock-to-Dock Time
FTT First Time Through
FCSD Ford Customer Service Division
FPS Ford Production System
FTPMM Ford Total Productive Maintenance
FR  Functional Requirements
ISPC In-Station Process Control
JIT  Just-in-Time
MCT  Manufacturing Cycle Time
MTBF Mean Time Before Failure
OTD Order to Delivery
OEE Overall Equipment Effectiveness
POS Plant Operating System
PTO Powertrain Operations
PPS Powertrain Production System
PV  Process Variables
QOS Quality Operating System
SHARP Safety and Health Assessment Review Process
SPC Statistical Process Control
TPM Total Productive Maintenance
VO Vehicle Operations
WIP Work-in-Process Inventory
 Appendix II  Measurables Survey

This appendix includes a copy of the survey form distributed to plant management at all manufacturing sites in North America and Europe. The two-page form was distributed to the designated measurables coordinators at each plant at the end of several training sessions, as well as through the Ford electronic mail system.
This survey is being distributed as part of a study for the Ford Production System. The survey is designed to get feedback from several layers of plant management on the current use of manufacturing measurables at their plant. It is being distributed to management in several divisions, both in North America and Europe.

We encourage you to participate in this study as an opportunity to provide feedback. The responses will remain anonymous. We appreciate your efforts in completing and returning this survey.

Name (Optional): __________________ Position or Job Title: __________________

Division: (ACD, EFHD, PTO, VO) __________ Location: (Plant, NA or Europe)________

Part A. Measurables Rating

Please Rate each of the measurable categories below for the AMOUNT and QUALITY of information available at your level of management, by circling a number from 1 to 7.

Also, please check the answer that BEST describes the FREQUENCY of measurables reporting. If not reported at your level of management, just leave blank.

<table>
<thead>
<tr>
<th>Measurable</th>
<th>Amount of information very little much</th>
<th>Quality of information very good</th>
<th>once per shift</th>
<th>daily</th>
<th>weekly</th>
<th>monthly</th>
<th>quarterly or annually</th>
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<td>D. Equipment Uptime</td>
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<td>E. Inventory Levels</td>
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<td>K. Overhead Expenses</td>
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<td>M. Employee Satisfaction</td>
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<td>R. Program or equipment launch timing</td>
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<td>S. Setup times</td>
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<td>T. Process flexibility</td>
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<td>1 2 3 4 5 6 7</td>
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<td>U. Preventative maintenance</td>
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<td>1 2 3 4 5 6 7</td>
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</tbody>
</table>

Comments:
Part B.
From the Measurables listed on the previous page, choose the ones which BEST match the description by writing the corresponding letter for the measurable (please list the top four):

1. MOST Useful for YOU in making decisions 1. 2. 3. 4.
2. LEAST Useful for YOU in making decisions 1. 2. 3. 4.
3. Used most often for continuous improvement activities 1. 2. 3. 4.
4. Used mainly for reporting purposes 1. 2. 3. 4.
5. Used to evaluate the performance of your subordinates 1. 2. 3. 4.
6. Used by your management to evaluate your performance 1. 2. 3. 4.

Where do you feel you need MORE measurables information to meet your objectives?

Which measurables information do you spend the most TIME on, either in data gathering or analysis?

Part C. Measurable Functions
Please RANK these measurables functions from 1 to 8, by putting a “1” by the most important function, a “2” by the second most important, etc.:

- External Reporting
- Operations Control and Improvement
- Performance Measurement and Evaluation
- Communication to Different Management Levels
- Project Evaluation and Capital Budgeting
- Product Costing for Product Line Decisions
- Influencing Behavior in the Organization
- Influencing the Worldview of the Organization

We thank you for your time in filling out this survey, and appreciate your feedback.
Please add any additional comments below.
### Appendix III  Survey Results

Tables of Results from the Measurables Survey

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103
| Survey Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Division      | A | A | A | A | A | P | V | O | P | V | O | P | V | O | V | O | A | A | A | A | A | A | A | A | A | A | A | A | A |
| Location      | NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA |
| Quality of Info | 7 | 7 | 7 | 5 | 6 | 7 | 3 | 7 | 5 | 6 | 7 | 5 | 6 | 7 | 6 | 7 | 5 | 7 | 4 | 7 | 6 | 7 | 5 | 6 | 4 | 9 | 5 | 9 | 6 |
| Avg.          | 5 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |

**Selected Comments - Which Measurables do you Spend the Most Time on?**

**QUALITY DATA**

QUALITY, PRODUCTION VOLUME
QUALITY, PRODUCTION VOLUME
PRODUCTION VOLUME, QUALITY, EMPLOYEE SATISFACTION
INVENTORY, SCHEDULES
FIRST TIME THROUGH, OEE
INVENTORY LEVELS, PRODUCTION COSTS
PRODUCTION COSTS
LAUNCH TIMING, MEETING BUDGET
COSTS
QUALITY
QUALITY, UPTIME ANALYSIS
VOLUME, QUALITY, LABOR EFFICIENCY, LAUNCH TIMING
MEETING BUDGET
TOTAL COST BY VEHICLE
QUALITY
QUALITY, MACHINE UPTIME, MACHINE EFFICIENCY
QUALITY, CUST. SAT.
QUALITY, MEETING BUDGET, CUST SAT.
| Survey Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Division      | A | A | A | A | A | P | V | O | P | V | O | P | V | O | V | O | A | A | A | A | V | O | P | A | A | A | A | A | A |
| Location      | NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA| NA|
| A Reporting Freq. | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| B Reporting Freq. | 2 | 2 | 2 | 2 | 5 | 2 | 4 | 4 | 4 | 4 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| C Reporting Freq. | 2 | 4 | 4 | 4 | 2 | 4 | 4 | 2 | 2 | 2 | 2 | 5 | 2 | 3 | 5 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| D Reporting Freq. | 2 | 2 | 3 | 3 | 4 | 4 | 1 | 3 | 3 | 4 | 3 | 2 | 2 | 3 | 4 | 3 | 4 | 4 | 4 | 2 | 3 | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
| E Reporting Freq. | 2 | 4 | 4 | 2 | 2 | 4 | 2 | 4 | 2 | 4 | 4 | 3 | 4 | 3 | 1 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 |
| F Reporting Freq. | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 4 | 4 | 5 | 5 | 4 | 4 | 3 | 3 | 4 | 4 | 3 | 4 | 3 | 3 | 4 | 3 | 3 | 3 | 3 |
| G Reporting Freq. | 3 | 4 | 4 | 4 | 2 | 4 | 3 | 3 | 2 | 2 | 2 | 4 | 2 | 2 | 2 | 2 | 1 | 2 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| H Reporting Freq. | 3 | 4 | 5 | 4 | 2 | 4 | 3 | 3 | 2 | 2 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| I Reporting Freq. | 2 | 2 | 2 | 3 | 4 | 1 | 4 | 3 | 4 | 3 | 3 | 3 | 4 | 4 | 2 | 4 | 4 | 2 | 4 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| J Reporting Freq. | 3 | 4 | 4 | 2 | 3 | 4 | 4 | 2 | 2 | 3 | 2 | 2 | 4 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| K Reporting Freq. | 4 | 4 | 4 | 2 | 3 | 4 | 3 | 3 | 2 | 2 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| L Reporting Freq. | 4 | 5 | 4 | 4 | 4 | 5 | 4 | 2 | 4 | 4 | 5 | 5 | 3 | 3 | 4 | 5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| M Reporting Freq. | 5 | 5 | 2 | 5 | 3 | 5 | 5 | 9 | 5 | 5 | 2 | 5 | 3 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| N Reporting Freq. | 3 | 4 | 4 | 5 | 4 | 2 | 4 | 3 | 4 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 4 | 3 | 3 | 5 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
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| P Reporting Freq. | 3 | 3 | 3 | 3 | 5 | 4 | 2 | 4 | 2 | 4 | 3 | 5 | 3 | 2 | 3 | 4 | 3 | 4 | 4 | 5 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
| Q Reporting Freq. | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 5 | 2 | 4 | 2 | 4 | 2 | 4 | 2 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| R Reporting Freq. | 4 | 4 | 4 | 5 | 2 | 4 | 4 | 3 | 4 | 4 | 3 | 4 | 4 | 3 | 3 | 4 | 2 | 3 | 5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| S Reporting Freq. | 4 | 4 | 3 | 4 | 4 | 2 | 4 | 2 | 5 | 2 | 3 | 2 | 2 | 5 | 2 | 5 | 2 | 5 | 2 | 5 | 2 | 5 | 2 | 5 | 2 | 5 | 2 | 5 |
| T Reporting Freq. | 5 | 5 | 2 | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 3 | 4 | 4 | 3 | 4 | 3 | 4 | 4 | 3 | 4 | 4 | 3 | 4 | 3 | 3 | 3 |
| U Reporting Freq. | 3 | 2 | 3 | 2 | 5 | 3 | 4 | 4 | 2 | 3 | 2 | 3 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 3 | 3 | 3 |

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**External Reporting**

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**Selected Comments - Where do you need more information?**

BUDGET PERFORMANCE AND PRODUCTION COSTS

PM, ABSENTEEISM, TOTAL COST
PM, PRODUCTION COSTS, CROSS-TRAINING
PM, PRODUCTION COSTS
PM
DELIVERY, SCHEDULING, DTD
QUALITY, CUSTOMER SATISFACTION, PM
UPTIME, MEETING BUDGET
TOTAL COST
UPTIME, MACHINE EFFICIENCY
EMPLOYEE SATISFACTION
References


