Strategies and Processes for Identifying and Resolving Throughput Problems in an Automotive Paint Shop

by

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B.S. Mechanical Engineering
Kettering University 1998

Submitted to the Sloan School of Management and
the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Mechanical Engineering
and
Master of Science in Management

in conjunction with the Leaders for Manufacturing Program

at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 2002

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Abstract

Automotive and other manufacturers have made a variety of attempts to implement lean manufacturing philosophies and principles into their manufacturing operations. Of critical importance in a lean system is the ability of the personnel in the lowest levels of the organization to recognize when the manufacturing system is not meeting its functional design requirements, identify the precise location and root cause of the problem, and develop and implement a permanent solution. This thesis will investigate methods to locate, resolve, and prevent throughput problems in both an existing system and a new design, and identify the processes, metrics, and feedback that is needed to facilitate the identification and resolution of problems at the lowest possible level. This thesis references throughput improvement activities that were conducted on an internship at the Ford Motor Company Kentucky Truck Plant paint department.

The thesis will examine the following areas:
- Background on basic Ford paint process (value stream, flow, and operating philosophies)
- Ford Production System strategy, and influences on operations in the paint shop
- Throughput bottleneck identification methods in an existing manufacturing system
- Functional requirements, design parameters, and performance metrics for a manufacturing system design with regard to throughput
- The information, communication, and data systems that enable the feedback of critical metrics to those who can act upon them
- Analysis of the Ford Production System, and how it does and does not facilitate problem identification and resolution

Thesis Advisors

Professor David Cochran, Department of Mechanical Engineering
Professor Thomas A. Kochan

Acknowledgements

This thesis represents the culmination of two of the most intense and challenging years of my life to date, and I would be remiss if I did not recognize those who made it possible. The Leaders for Manufacturing Program at MIT has exceeded my expectations, and has helped me to realize a level of achievement I never thought possible.

Thank you to the LFM staff, for this opportunity, and to my thesis advisors, David Cochran and Thomas Kochan, for their support of my project.

Thank you to Ford Motor Company for their support of the LFM Program and of this thesis research, especially Chris Tallon and the group at KTP. Thanks for allowing me to help leave your shop a little better than I found it.

Thank you to my LFM classmates. The combination of intelligence, intensity, and pure fun that exists in this group creates the environment that makes this program great. Best of luck in all your future endeavors.

Finally, and most importantly, I want to acknowledge my family for continuing to provide the most solid foundation one could ask for, and Kristin for keeping her faith in me during these two years. It will be worth it, I promise.

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Chapter 1: Introduction

Achieving production throughput levels to match customer demand is essential in any manufacturing system. In an automotive plant, producing to takt time in a consistent, stable manner becomes even more critical, since failure to do so results in expensive overtime costs, not just for one process or department, but possibly for several. In addition, the "fire-fighting" mode that often results from a production shortfall may sometimes cause a lack of proper attention to quality, safety, or other concerns.

This thesis describes various methods for managing throughput in a manufacturing system, from the viewpoint of both analyzing an existing system and designing a new system. Also, metrics are developed that correspond to the system design at various levels of detail, and a proposal is made for a cohesive design of an information feedback system, to allow these metrics to be used effectively in the continuous improvement of the system. The stated goal of this system is to make the manufacturing system's performance transparent to all persons responsible for improving it, facilitating the development of self-managed work groups and an overall learning environment in the organization.

This thesis makes many references to lean manufacturing concepts, as the proposed methods are most applicable to organizations that have adopted lean principles, tools, and structure, such as a flow-based system, continuous improvement production work groups, and visual control systems. However, very little of the literature on lean manufacturing deals with the challenge of using information to foster a learning environment, so this will be discussed. Additionally, the Ford Production System processes and metrics will be reviewed, specifically referencing a formal survey of production workers, to highlight the strengths and weaknesses of the processes and metrics in analyzing and improving throughput and in fostering a learning environment.

1.1 Background

Since 1996, Ford Motor Company has been working to transform its manufacturing organization and processes from a mass production to a lean production concept using the Ford Production System (FPS). FPS was created to formalize the lean principles, developed by Toyota and described by Womack, Shingo, Monden, et.al., as they applied to Ford.

Of day-to-day concern to plant and area management in a manufacturing plant is production throughput relative to customer demand or takt time. Ford designates this as Delivery, and actively manages it along with five other key elements of manufacturing management: Safety, Quality, Cost, Morale, and Environment.

This thesis references activities that were conducted as part of an internship at the Ford Kentucky Truck Plant (KTP). The project specifically focused on improving throughput in the paint process, but a secondary goal was to demonstrate how FPS principles and metrics could be used to analyze and improve throughput, and also to determine where the Ford Production System might be improved to better foster this type of activity.

1.2 Thesis Objectives

This thesis has four primary goals. First, it provides a survey of various methods of analyzing throughput and determining throughput bottleneck(s) where improvement efforts should be concentrated. A structured approach is recommended that requires minimal performance data and applies best to the automotive paint process and processes with similar characteristics, namely serial flow layout, with some reentrant and rework flow, and little scrap. Second, an axiomatic design is proposed for a manufacturing system that produces at takt time in spite of inherent variation in the system. This design also describes the performance metrics that should be present to manage the system to its requirements at each level of detail in the design: production teams, engineering and plant management, and production system design. Third, a process is proposed for effective information feedback to production teams and engineering / area management, in order to facilitate the quick identification and resolution of problems, and foster a learning environment where continuous improvement can occur at the lowest levels of the organization. Fourth, the Ford Production system is critiqued, with regard to its ability to accomplish each of the first three goals.

1.3 Thesis Overview

An overview of the thesis follows.

Chapter 2 provides a general description of the Ford plant and the paint system that was analyzed as a part of this project, and also gives a more in-depth look at the Ford Production System and its role in the management of the paint system.

Chapter 3 provides a survey of various methods that have been proposed to analyze throughput and determine the location of throughput bottlenecks in a manufacturing system. These methods are critiqued with respect to their applicability and usefulness in the Ford paint system. Recommendations are made regarding the most appropriate methods. Actual data is disguised.

Chapter 4 describes an axiomatic design of a manufacturing system with regard to throughput, describing the functional requirements of the system, the design parameters that are used to accomplish the requirements, and the measurements that must be present to monitor the design parameters at each level of detail.

Chapter 5 describes a proposal for an information feedback system, which intends to make the manufacturing system transparent, communicate the measurements from Chapter 4 to those who can make use of them, make apparent the cause-effect relationships between inputs and outputs in the system, and foster an environment of learning and continuous improvement. A survey of production workers within Ford is used to highlight weaknesses and possible improvements of the Ford Production System in this regard.

Chapter 6 summarizes the conclusions developed in the thesis, with recommendations for the Ford Production System and the Kentucky Truck paint department.

Appendix A shows a formulation for a binomial probability algorithm that can be used to consider expected cycle-time variation at an individual conveyor line operation. Using this formulation, one can design an optimal work zone length to prevent throughput loss due to operator line stops.

Appendix B shows the survey questions given to production workers as a part of this research, describes the survey and selection method, and gives some worker responses to each question.

1.4 The LFM Internship

This thesis was developed based partially on research that was conducted during an internship at Ford Motor Company's Kentucky Truck Plant in Louisville, Kentucky, specifically working in the Paint department of the plant. The internship was coordinated through the Leaders for Manufacturing Program at MIT. While much of the material in the thesis is adapted from the literature, the adaptation is grounded in either work or research done at the plant site, and specific focus is given to how the material applies to the Kentucky Truck Plant Paint department. Lessons developed from both the literature and practical experience are included, and delineated where appropriate.

Chapter 2: The Automotive Paint Process and the Ford Production System

The first part of this chapter gives background on the Ford Kentucky Truck Plant and a general description and key features of the paint system at KTP. The latter part discusses the Ford Production System, its history, implementation scheme, and the evidence of FPS that could be observed within the paint system.

2.1 Kentucky Truck Plant

The Kentucky Truck Plant is one of two Ford plants located in Louisville, KY. Originally it produced heavy commercial trucks, until Ford exited that business. It now manufactures a limited volume of Excursion sport-utility vehicles, but primarily builds Super-Duty F-Series pickup trucks along with another plant in Cuautitlan, Mexico. Numerous model varieties of the Super Duty truck are produced, with regular, super, and crew cabs, engine and transmission options, 6', 8', or no box, and dual- or single-rear wheels.

The plant operates 12 shifts per week, two per day during the week, and one per day on the weekend. During the week 1½ hour is scheduled between shifts, with 13½ hours between shifts on the weekend. Three production crews work at the plant, each working four shifts per week.

The plant's manufacturing process is similar to most others one would find in a truck plant. The plant is divided into five major departments or areas, each of which is managed somewhat independently from the others. Figure 2.1 shows the overall process. Vehicle build begins in the body shop, which assembles and welds sheet metal stampings that come from an on-site stamping plant and from external sources. The assembled body-in-white then moves to the paint shop, where it is painted and body seams are sealed. Then the trim department assembles the interior components and external trim of the vehicle. The chassis line assembles the chassis and powertrain of the vehicle, from externally acquired frames, engines, and transmissions. Finally, the body and chassis are joined and the final assembly process completes the assembly of the vehicle. Each department is somewhat decoupled from the others, because of large work-in-process buffers that separate them.

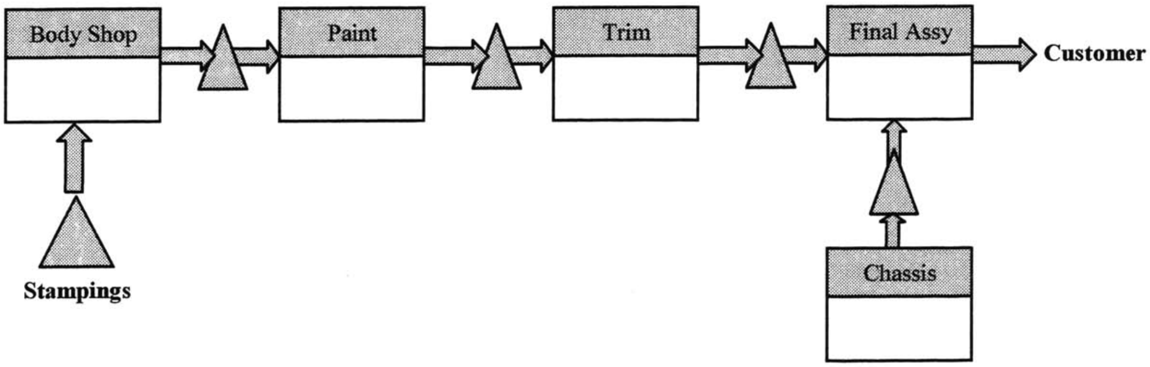
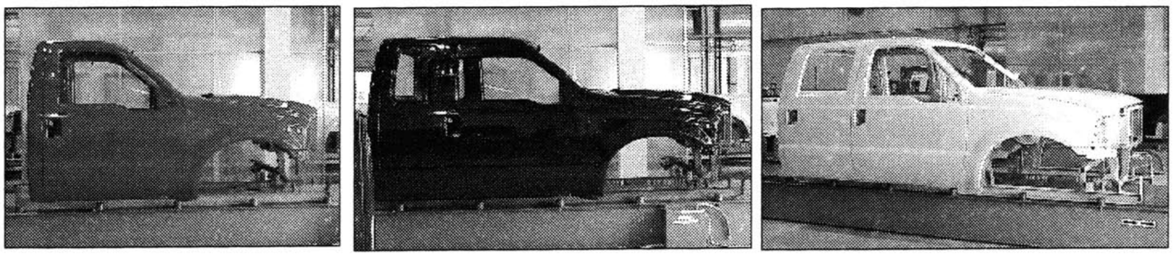


Figure 2.1 KTP Super Duty Truck Basic Manufacturing Process

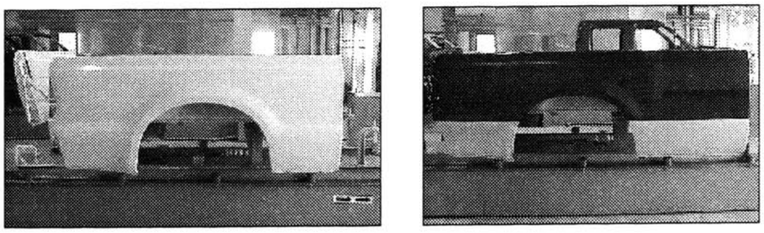
2.2 The Paint System

The paint system takes assembled body-in-white cabs and boxes, and produces finish painted units in any of 10-15 monotone colors and several tutone color schemes. The model mix as relevant to the paint shop is shown in Figure 2.2. Three cab styles and two box styles (or no box at all, for a custom conversion vehicle) can be used to form a truck. The cabs and boxes are on separate transfer skids, although a box typically arrives at the paint shop immediately behind its matching cab.

The vehicles are processed through three paint stages, as well as a sealing process, several inspection stations, and a black spray operation. Figure 2.3 shows a detailed process map of the paint system.



Regular Cab Super Cab Crew Cab



6' Box 8' Box

Figure 2.2 KTP Paint Shop Model Mix

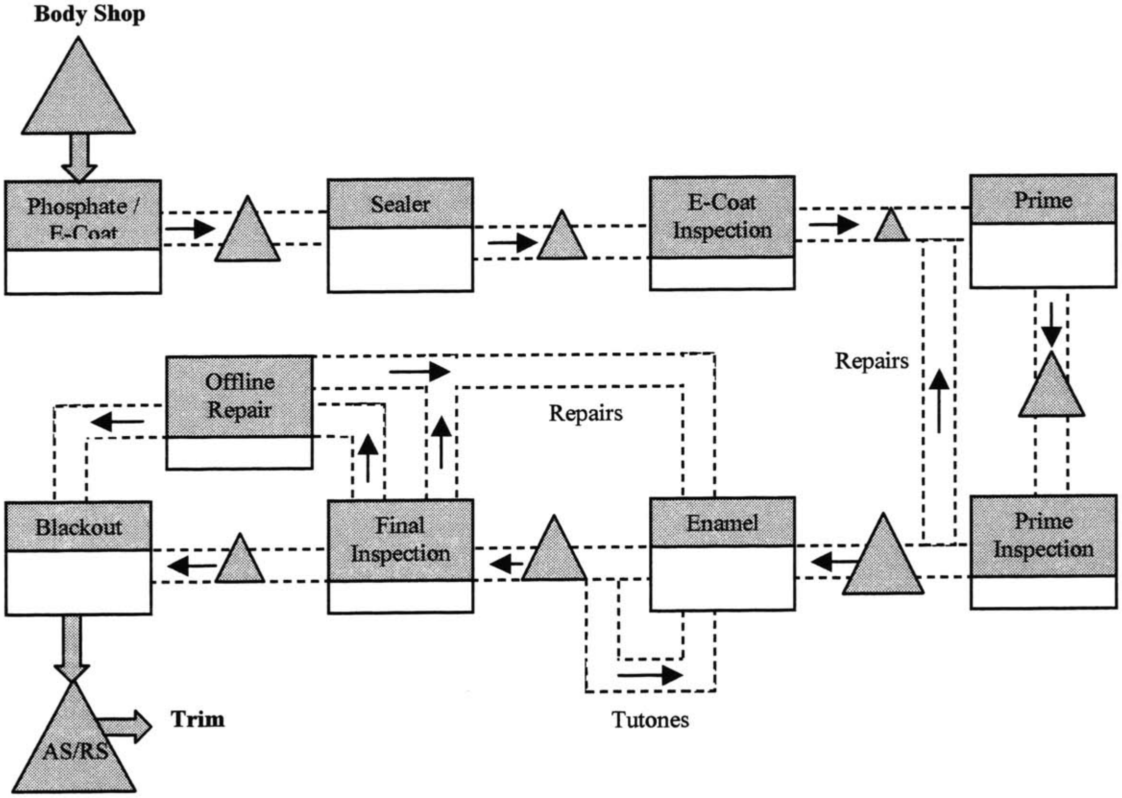


Figure 2.3 KTP Paint Shop Process Map

The process begins with a phosphate cleaning process to remove dirt and oil from the sheet metal surface, and then an electro-coat painting operation to provide corrosion resistance.

The vehicle then moves through a sealing process, where putty-like sealant is applied to various body joints to prevent water leaks. This sealant is applied both manually and using robotic automation. The e-coat inspection booth is next, where bright fluorescent lighting allows several inspectors to detect any defects in the e-coat paint. Any dirt or defects are lightly sanded away. Next the truck moves into the prime spray booth, where people and automation apply a coat of prime paint. The vehicle then goes through a prime inspection booth, very similar to the e-coat inspection. If the unit passes inspection, it proceeds to the enamel spray booth, where both basecoat and clearcoat are applied, again using both manual sprayers and automation. Then comes a final inspection booth, and finally a coating of black spray is applied to the front of the body to prevent any color from showing through the grill of the finished vehicle. A continuous-flow oven follows each of the three paint stages, as well as the sealing process, and performs a finished bake of the paint or causes the sealant to gel.

There are several points in the process that see reentrant flow and rework flow. Units that fail the prime inspection are redirected through the prime spray process a second time. After the enamel spray process, tutone units are masked with plastic sheet and directed back through the enamel process to receive the second paint color. Units that fail the final inspection are either directed to an offline spot repair area, for minor defects, or to a repair line, for more serious defects. Vehicles that travel through the repair line are then directed back through the enamel process for a second coat of paint. Very few trucks are completely scrapped; the ones that are usually contain major sheet metal damage or have too many rework coats of paint applied.

Chain conveyors transfer the cabs and boxes from one process to the next. In addition, each process area is separated from adjacent processes by decoupling buffers, consisting of either banks of chain conveyors or single accumulating chain conveyors. These buffers vary dramatically in size, which is represented in Figure 2.3 by the relative size of the WIP symbol.

The paint process in an automotive plant is inherently difficult to control. Many process and environmental parameters have an affect on the finished product, which is then held to extremely high standards of quality. One speck of dirt, airflow disruption, paint viscosity variation, or manual sprayer misstep, and the paint finish is unacceptable. World-class paint systems might still only produce 85-90% units that require no repairs at all. The enamel spray process is designed with significant additional capacity, to account for this rework flow.

To control this process, many actions are taken to prevent environmental and process related causes of defects. The shop is maintained at a positive air pressure, to keep dirt outside. All personnel in the shop are required to wear lint-free coveralls and hats. Special gloves must be used when touching the vehicle, and there is an extensive list of deodorants, hairsprays, and other personal care products that are prohibited for use by paint shop workers. Paint sprayers typically have significant experience and training for their job, although there is no separate union classification. Inspectors and repair operators likewise have much experience and training in their position. Paint sprayers, inspectors, and repair operators are not positions that can easily be filled by workers inexperienced in these areas. In the paint booths, airflow, temperature, and humidity are tightly controlled, and highly trained operators monitor and adjust the automation.

2.3 The Ford Production System

The Toyota Production System has been the subject of intense study in one way or another for the past 15-20 years. In their landmark 1991 book, The Machine That Changed The World, Womack, Jones, and Roos highlighted Toyota's system as fundamentally different than traditional Fordist mass production, and declared that this system was the way of the future.[1] By 1997, all of the Big Three U.S. automotive manufacturers declared unequivocally that they were transforming all of their manufacturing to their own versions of TPS (Liker, 1998, p. 6). Ford Motor Company was no exception, and along with other strategic goals that were given the moniker "Ford 2000," the company's management began a massive effort to transform their manufacturing systems and culture to a set of principles they called the Ford Production System.

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[1] Although the authors never mentioned Toyota by name.

Ford was no stranger to operational improvement. After a near-death crisis in the early 1980's, extensive focus was put on improvements in manufacturing quality and productivity. One of the key initiatives, which was ground-breaking for Ford, was called Employee Involvement (EI). This program, supported by the United Auto Workers national union, involved shop floor level workers in problem solving and quality improvement efforts through paid meetings and training in teamwork and problem-solving skills.[2] These efforts, as well as significant capacity and workforce reductions, elevated Ford to be among the highest-rated automakers in the world. From 1980 to 1988 the quality of Ford cars and trucks improved by 65 percent, mainly due to the efforts of people, not through improvements in automation. A 1995 Customer New Vehicle Quality Survey ranked Ford ahead of GM and Chrysler and just behind Toyota in customer satisfaction, and the 1995 *Harbour Report* on labor productivity ranked several Ford plants almost identical with Toyota's Georgetown plants (Liker, 1998, p. 12-13).

Despite this success, Ford's top management can be credited with recognizing that it was not enough. The focus on quality did little to reduce waste in the manufacturing process, there was no focus on manufacturing lead-time or equipment reliability, and much of the worker productivity could be attributed to enormous amounts of overtime worked by Ford employees. It was clear that this situation was not sustainable or sufficient, and the organization needed focus for the future.

2.3.1 What is the Ford Production System?

This is not easy to answer, and it is not at all surprising that few people within Ford can give a clear, succinct answer to this question. At its core, the principles of FPS are fully consistent with those of TPS. However, it is necessary to communicate these principles to those within Ford who must implement and use them, and it is worthwhile to show how Ford accomplishes this. At the highest level is a vision. The FPS Vision is:

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[2] This was so much of a cultural milestone that some hourly workers at KTP still refer to their FPS team meetings as "EI" meetings.

> 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.

This vision gives some clues as to the elements that Ford management feels are important in their production processes. A more detailed depiction of the vision and the elements that are required to create it is captured in the FPS Gear Model, shown in Figure 2.4.

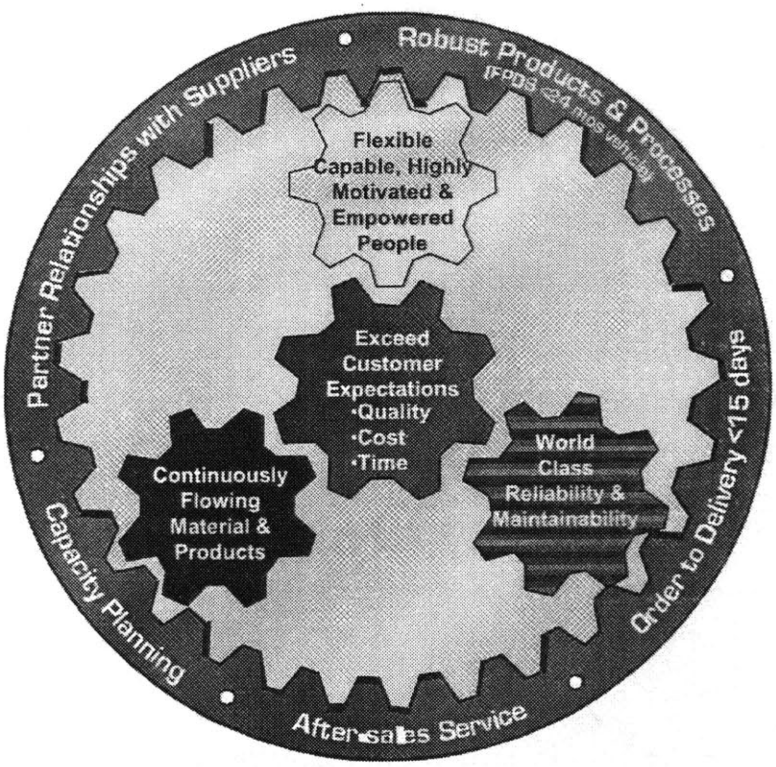

Figure 2.4 FPS Gear Model

In this model, the center represents the core goal, exceeding customer requirements. The three pinion gears show the key elements that need to be in place to achieve that goal, and the outer ring represents the supporting systems that tie the production system together (Liker, 1998, p. 16).

2.3.2 FPS Implementation

The Gear Model shows how FPS should work. The next step is to detail the specific implementation directives to get from the current state to the ideal FPS vision. These directives or programs are divided into eleven[3] areas, described very briefly and incompletely as follows:

- Environmental – Denotes conformance to environmental regulations, ISO 14001 standards, and corporate policies.
- Ford Total Productive Maintenance (FTPM) – Production workers are involved in preventative maintenance and cleaning of equipment, to enhance machine reliability and prevent unplanned downtime.
- Industrial Material Flow – Streamlines the flow of indirect materials used in the plant.
- In-Station Process Control – Ford's version of jidoka and poke yoke, promoting the recognition of defects within the workstation in which they were created.
- Managing – Encourages plant management to use FPS principles, tools, and metrics in the normal operation of the plant.
- Manufacturing Engineering – FPS principles, tools, and metrics are applied to equipment purchase, installation, and operation.
- Quality – Represents a number of physical and process related quality procedures.
- Safety and Health Assessment Review Process (SHARP) – Deals with employee safety, emergency procedures, ergonomics, and other safety related issues.
- Synchronous Material Flow – Implementation and optimization of a kanban-based pull system for component parts, dealing with both internal and external logistics.
- Training – A plan for determining, satisfying, and tracking the training needs of employees.
- Work Groups – Describes the structure of production worker teams, and the actions and responsibilities these work groups should have.

The eleven elements are each laid out in an implementation sequence, which describes the accomplishments or milestones that designate progress in their implementation. Each element

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[3] Originally (as described in Liker), only seven programs existed. Environmental, Managing, SHARP, and Training were either added later or integrated from other programs within Ford.

has five general phases, which are virtually the same as in the process used by the Toyota Supplier Support Center (Liker, 1998, p. 20).

1. Stability
2. Continuous flow
3. Synchronous Production
4. Pull System
5. Level Production

A matrix called an Integrated System Review or ISR matrix gives a numerical 1-10 rating for each of the milestones along the implementation path, giving more detailed refinement than the five steps listed above and allowing a plant's progress to be tracked and scored. Additionally, each element contains a wealth of manuals, training programs, and other materials that can be used by the manufacturing plants to aid in their progression in the eleven areas.

2.3.2 FPS Metrics

Along with the implementation elements and plan, Ford also developed a new set of process performance measurables for use in evaluating manufacturing plants and plant management with regard to their improvement in the areas that are critical to FPS. There are six key measurables, described here as paraphrased from Liker:

1. Work Group Effectiveness – This is a rather fuzzy metric, but includes ratings from employee surveys regarding communication, teamwork, decision-making, employee suggestions, and safety.

2. First Time Through Capability (FTT) – A quality measure of what percentage of products go through the process the first time, without need for rework, rerun, offline repair, scrap, or other diversion from the normal production flow.

3. Dock-to-Dock Time (DTD) – This is a measure of throughput time within the plant, from unloading of raw materials to shipping finished product. This measure is meant to drive the reduction of non-value-added time in the system.

4. Build-to-Schedule (BTS) – The percentage of units that are produced on the correct day in the correct sequence, as defined by the customer-driven build schedule. It promotes building the right quantity at the right time.

5. Overall Equipment Effectiveness (OEE) – This is a composite measure representing overall percentage utilization (not including scheduled downtime) or throughput efficiency. OEE is a system-level metric that includes every reason why a process is not producing to its rated capacity.

6. Total Cost – The combined cost of material, labor, overhead, freight, inventory, fixed costs, assessments, and all other costs incurred by the manufacturing plant. It is meant to focus personnel on more than just the traditional and often inappropriate measures of labor and overhead cost.

These measurements were designed for use by all levels of the organization, from upper management to production floor teams. Their effectiveness and usefulness for this purpose will be discussed further in Chapter 5.

2.3.3 The Role of the FPS Group

The central FPS group within Ford that developed the FPS vision and implementation plan does not have direct responsibility over the plant managers to force or direct them to implement the FPS program. They have provided management with a set of measurables, to which the plant managers can be (and mostly are) held accountable in their performance evaluations, and they provide training and manuals to aid the plants in learning how to implement the methods. They also conduct performance audits on a regular basis, and give plants a total composite score from 1-10 that represents their performance in implementing FPS and allows them to be compared with other Ford plants. Most employees at the Kentucky Truck Plant were aware of the plant's rating on the most recent audit, and also were aware of the ratings of various other plants. Highlights of these audit results were typically published in company newsletters.

2.4 Evidence of FPS in the Paint System

In the paint shop at KTP, FPS manifests itself in several ways, including the work group structure, performance measurements, and plant-wide steering committee meetings. Work groups, called Continuous Improvement Work Groups (CIWG) were the most visible feature. The workers in each process area of the paint department were grouped in teams that met each week at the beginning of a shift to discuss any changes, problems, or improvements that were being conducted in their area. The skilled trades and paint booth operators each formed a team as well. Each team had its own office area or conference room to conduct its meetings, and had a wealth of data and performance measurements related to their process or the department's performance. Elected members of the team facilitated the meetings, and workers were encouraged to bring up problems and improvement suggestions, which were then recorded and assigned to appropriate persons to be managed. Workers needed the approval of engineering or management to make any major changes to the process or incur significant cost, but there was also a process by which the team could elevate an unresolved issue all the way to the plant manager if necessary. The skilled trades work group was very involved in the design and implementation of process changes in the plant.

Performance measures were charted and reported to the work teams, but also were recorded for the department as a whole. The FPS measures like DTD, OEE, Total Cost, and Quality (internal and external) were recorded and displayed periodically. The OEE measure was recently beginning to be used for control purposes, analyzing the system and directing improvement efforts. Many of the quality measures were starting to be tracked and reported by computer. Most of the other measures were used simply for reporting purposes.

The other noticeable manifestation of FPS was the plant-wide steering committee meetings, run by the plant manager. Each department was expected to report on its critical metrics, any special projects it was involved in, or any notable accomplishments.

There were many other manifestations of FPS that were present in the paint shop, but were not readily apparent or have a significant effect on the daily operation. The sheer amount and complexity of fixed automation in the plant made it very difficult to rearrange process flows or drastically alter the plant layout as might be done in other lean implementations. In other areas of the plant, where there are more incoming component parts, kanban cards and standard inventory locations were a very obvious sign of Strategic Material Flow being used.

Chapter 3: Bottleneck Identification and Throughput Improvement

The manufacturing system in an automotive assembly plant is typically arranged in a serial flow, with successive processes arranged sequentially. In order to improve throughput in this type of system, one must first determine the points of highest leverage in the system, where making improvements to process performance will result in the largest increase in total system throughput. This will allow management to focus limited resources on the areas that will have the greatest impact. Most people refer to the point of highest leverage as the "bottleneck," which is the process that is most constraining the throughput flow. Goldratt (1990) uses this principle as the basis for his Theory of Constraints, and claims that identifying and exploiting the bottleneck is the key to improving system throughput.

The paint system at Ford KTP fits this model of serial flow and sequentially arranged processes. A primary goal of the internship assignment was to identify the throughput bottleneck(s) and implement a plan to increase system throughput. Achieving this would result in a reduction of overtime hours required to meet customer demand, as well as the ability to flex to customer demand for vehicles that required more capacity per unit (crew cabs, cabs with boxes, and tutone trucks). The approach, then, should be to find the system bottleneck and focus on improving it or increasing its capacity.

However, while Goldratt's approach is useful conceptually, it is more difficult to make practical use of it. There are two primary problems.First, while he presents a clear process for improving throughput, the methods for identifying the location of the system bottlenecks are less well developed (Longcore, 1999, p. 10). He recommends observing the system to see where work-in-process accumulates. In some systems, this is difficult or impossible to observe. Second, Goldratt's approach leads one to believe that there is typically only one system bottleneck, and even goes so far as to recommend that the system be designed with a bottleneck process. This is not very applicable to an automotive assembly system. In most plants, successive processes are fairly well balanced in capacity, such that bottlenecks in the system are really transient. One process may have the least throughput in the morning, while another may constrain the flow in the afternoon. One tends to see multiple bottlenecks due to large system variation stemming from machine complexity and the balanced design cycle time of assembly processes (Schulist, 1997, p. 19). Over time, one process may emerge as causing more throughput loss than any other, but typically each process contributes somewhat to overall throughput loss. Likewise, making improvements to any process will likely result in an increase in total throughput (not just making improvements at the primary "bottleneck").

Ideally, what is needed is an analytical or heuristic process to:

1. Identify the contribution of each process to the total loss in system throughput.
2. Allow for the fast iterative analysis of improvement scenarios, to develop a definitive action plan that will result in the achievement of system targets.
3. Require as little data collection as possible to achieve #1 & #2.

The following sections will review and evaluate various techniques that have been developed to locate bottlenecks and analyze system throughput. The recommended approaches used in Ford's paint shop will be given, and the tools used to improve and facilitate the improvement of throughput will be discussed.

3.1 Bottleneck Analysis Techniques

Numerous techniques have been developed for the purpose of finding the bottleneck. Six of these will be reviewed here, with an evaluation of the strengths and weaknesses of each. The actual data shown in the following sections is disguised.

3.1.1 Ford Capacity Analysis Procedure

Ford's FPS instruction manuals describe a method for locating bottleneck(s) within a manufacturing system. This procedure makes use of three pieces of data for each process: gross capacity rate, hours worked per shift, and Overall Equipment Effectiveness (OEE). Recalling from Chapter 2, OEE is a percentage measure of total equipment utilization during scheduled running time, taking into account every reason why a process is not producing to its rated capacity, including downtime, yield/rerun rate, slow cycle time, blocks, and starves.

Multiplying these three numbers together yields the total production per day for each process, as shown in Figure 3.1. The procedure states that the process with the lowest total throughput is the system bottleneck.

Process	**Gross Capacity (jobs/hr)**	**x**	**Hrs. Worked / Shift**	**x**	**OEE**	**=**	**Net Throughput / Shift**	
Phosphate/E-Coat	56		9		88.0%		444	
Sealer	52		9		91.2%		**427**	#2 Bottleneck
E-Coat Inspect	58		10		80.1%		463	
Prime	57		10		81.3%		463	
Prime Inspect	60		10		78.2%		469	
Enamel	75		9.5		57.2%		**408**	#1 Bottleneck
Final Inspect	57		10		75.8%		432	
Blackout	60		10		75.4%		452	

Figure 3.1 Ford Capacity Analysis Procedure

This analysis method is not an accurate means to determine the system bottleneck in a system where there is appreciable interaction between processes (blocks and starves). The Ford paint shop is such a system. Since OEE is a measure of total utilization, it stands to reason that the net throughput per shift should be the same for every process (neglecting the effect of scrap or yield loss, which is minimal in the paint process). For example, if an average of 450 vehicles enter the paint shop each day, then an average of 450 vehicles should travel through each process in the system. OEE also accounts for reentrant and rework flow, so this will not show up in Net Throughput / Shift. In fact, assuming that all of the data are completely accurate, the only reason that Net Throughput / Shift would be different from one process to another is if units leave the flow (i.e. scrap). However, even then the lowest result does not represent the location of the bottleneck.

In reality, the reason this analysis results in different numbers for Net Throughput / Shift is that the data (primarily OEE) is not completely accurate. An additional problem with this method is that it cannot be used to analyze throughput improvement scenarios. In a system with interactions between processes, the OEE of one process depends on the operating characteristics of all the surrounding processes. Changing any of the three parameters for one process may result in a change in the OEE of the other process.

This method is relatively simple, and may be used effectively where successive processes in a system are highly decoupled, meaning that the buffer size between processes is sufficient to ensure no blocking or starving. However, it is a totally inappropriate method for the paint shop system.

3.1.2 Flow Monitoring

Monitoring the flow through the system is most like the method used in Goldratt (1990). The location of the worst system bottleneck is determined by where work-in-process inventory accumulates. In The Goal, the bottleneck location was obvious, more than likely consistent from day to day, and in a location where WIP could accumulate. In an automotive assembly process, it might be more difficult to observe this, if the flow is complex or WIP cannot accumulate.

Another way to analyze the system using this method is by recording the blocked and starved time for each process, as shown in Figure 3.2. The average blocked and starved time per shift can be plotted for each process. If there is one consistent, defined bottleneck, that process will be the transition point where blocked time decreases and starved time increases.

As is shown in Figure 3.2, the result is rarely that clear cut. In the paint process, there is a general area where this transition occurs, and the primary bottleneck is obviously somewhere in this area. The data can also be clouded by blocks and starves that occur from local interactions in the system. In the Ford paint shop, a strong local interaction existed between the E-Coat Inspection and Prime processes, due to the very small buffer between these two. It is not clear then where the primary bottleneck is located.

An additional limitation of this method is that it only locates the primary bottleneck, and serves to reinforce the notion that process improvement should only be focused on one process. Additionally, there is no way to determine the specific level of process improvement needed to meet the target for the system.

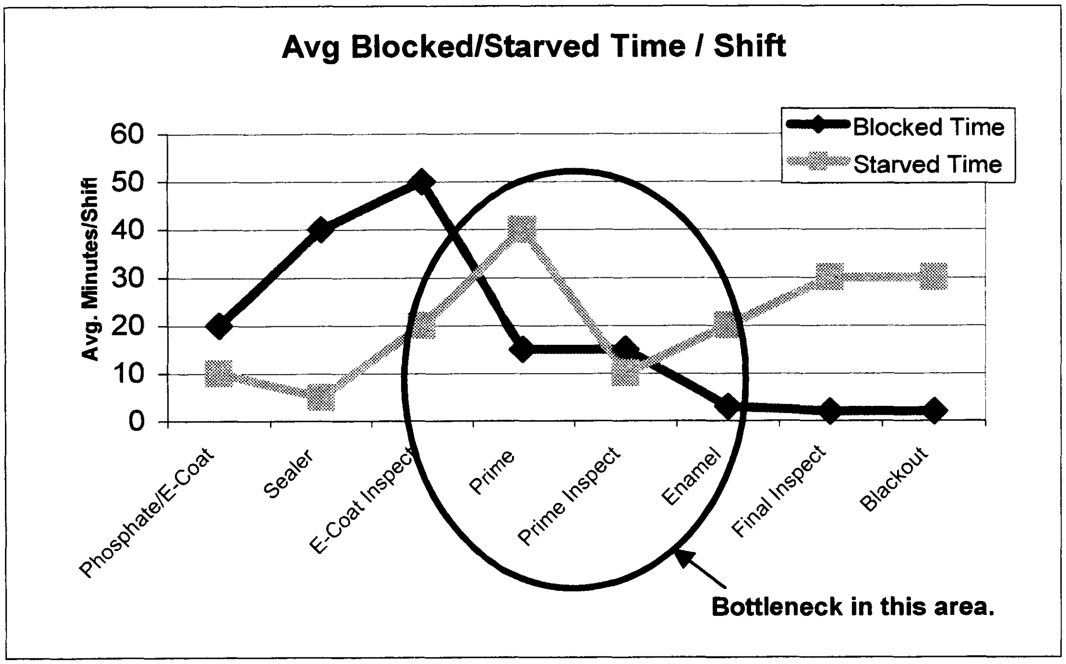

Figure 3.2 Flow Monitoring

One major advantage of this method is that it is easy to perform. Although blocked and starved data is often the most difficult process data to obtain, no other data are needed to conduct this analysis. This method could be helpful in performing a quick initial review of the system, when other process data is not available.

3.1.3 Gershwin Method

Professor Stanley Gershwin at MIT has developed an analytical approach to calculating the throughput of a manufacturing system that consists of sequential flow processes separated by decoupling buffers. The detailed methodology is described in Gershwin (1994), and an overview is given in Schulist (1997, p. 16-19). The method uses a combination of Markov processes, discrete-state random processes that describe the up or down state of each process, and a modification of M/M/1 queuing theory, which describes the bounded accumulation and draw down of parts in the buffers between processes. The Mean Time Between Failure and Mean Time To Repair is required for each process. Using this approach, the net throughput of the system can be calculated, as well as the average quantity of units in each buffer.

When the algorithm is programmed into a computer, this method is impressive for the sheer speed at which it calculates the results. Essentially, it generates the same output as a throughput computer simulation model, without the time that it typically takes to build or run a simulation. Multiple scenarios can be tested quickly, to determine the exact benefits of process improvement in each area.

This analysis method does not give a definitive answer as to the location of the bottleneck(s), or their relative contribution to overall throughput reduction. However, the analysis is fast enough that improvements to every process can be input, and the improvement in overall throughput recorded. Another limitation of this approach is that it can only model simple systems. Gershwin has developed the ability to consider processes with less than 100% yield rates, but the tool cannot calculate the effect of reentrant flow or multiple part types in the system. Since the Ford paint shop works with several different part types and significant reentrant flow, the use of this approach would be limited to local areas where the impact of these factors was minimal.

3.1.4 C-More (General Motors)

General Motors uses a software package called C-More for throughput analysis. C-More is a bottleneck analysis tool developed by the GM Research Center for use in GM assembly plants. This proprietary software predicts where bottlenecks occur in a system and the impact to total system throughput of improving the bottleneck processes (Schulist, 1997, p. 55). This software was developed with help from MIT professor Steven Graves, among others.

Process	Throughput Loss (jph)
Enamel	5.2
Prime	4.8
Sealer	2.2
E-Coat Inspect	2.1
Blackout	0.5
Prime Inspect	0.4
Phosphate/E-Coat	0.3
Final Inspect	0.1
Gross Capacity Constraint (Sealer) Capacity --	**52**
Total Throughput Loss --	**15.6**
Net System Throughput --	**36.4**

Processes ranked in order from highest to lowest bottleneck.

Figure 3.3 C-More Sample Output (adapted from Schulist, 1997, p. 59)[4]

Although little information is publicly available about the analytical methods used by C-More, it appears to use similar algorithms as the Gershwin approach. C-More predicts the net throughput of a system, and also performs an iteration for each process, improving its uptime and yield to 100%. For each scenario, the increase in net throughput is recorded. The processes are then ranked according to the contribution of each one to the total loss in system throughput. A

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[4] C-More is a proprietary General Motors software package, and was not used in the Ford paint shop. This figure shows what the results might have looked like if the tool were used.

sample output, as it might look if it were run in the Ford paint shop, is shown in Figure 3.3. The results of other improvement scenarios can also be calculated quite quickly.

Although C-More gives a more detailed level of output than Gershwin, it seems still subject to the same limitations as that method, with respect to reentrant flow and multiple part types. As such, it is a highly efficient way to analyze throughput, which may not be completely accurate depending on the process. Additionally, the literature (Schulist, 1997, Cassidy, 1999) refers to C-More being used primarily for macro level throughput analysis, while micro level analysis for various stations of one particular process is performed by other methods. It is unclear why this is the case.

3.1.5 Cassidy Approach

Cassidy (1999) developed a bottleneck analysis approach that is somewhat unique from others that have been discussed. Cassidy analyzed an automotive body shop system, with the desire to achieve the same type of result as given by C-More, namely the contribution of each station or process to the overall loss in throughput. Cassidy (1999, p. 61-66) describes this model in detail.

This method focuses the analysis on the gross capacity constraint in the system. First, the utilization (or OEE) of the gross capacity constraint is determined, and the loss of throughput is divided into its various components, including downtime, quality reruns, starved, and blocked. The gross constraint is measured since it is the only process that can theoretically achieve 100% utilization[5]. One can then see what is causing lost throughput at this process, and focus on improving it.

If downtime or quality is a large contributor to lost throughput, then resources are best focused on improving that process. If the gross constraint is blocked or starved most of the time,

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[5] Although achieving 100% utilization is rarely the goal.

the analysis must be taken one step further. The blocked or starved time is assigned to individual upstream or downstream processes, using block and starve data from each of these processes.

In the example shown in Figure 3.4, the largest component of lost throughput is blocked time, so that blocked time is assigned to each downstream process. Now one can see that Enamel, Prime, and E-Coat Inspect each contribute to significant throughput loss, and resources can be focused on these areas.

The algorithm for assigning the blocked or starved time is relatively simple, and assumes that blocks travel upstream and starves travel downstream. To distribute the blocked time, one would start at the furthest process downstream from the gross constraint, in this case the Trim Shop. The formula for determining this value is:

Sealer_Blocked(Trim) = Min (Blackout_Blocked, Final Inspect_Blocked,
Enamel_Blocked, Prime Inspect_Blocked, Prime_Blocked, E-Coat
Inspect_Blocked, Sealer_Blocked)

"Blackout_Blocked" represents the amount of time the Blackout process was blocked by the Trim Shop. Similarly, "Final Inspect_Blocked" represents the amount of time the Final Inspect process was blocked by Blackout. Sealer blocked time will only be allocated to the Trim Shop if that block traveled all the way upstream to Sealer. We assume that blockage flows upstream, and that any blockage assigned to the Trim Shop is the minimum of the blockage experienced by each off the processes between the Trim Shop and Sealer.

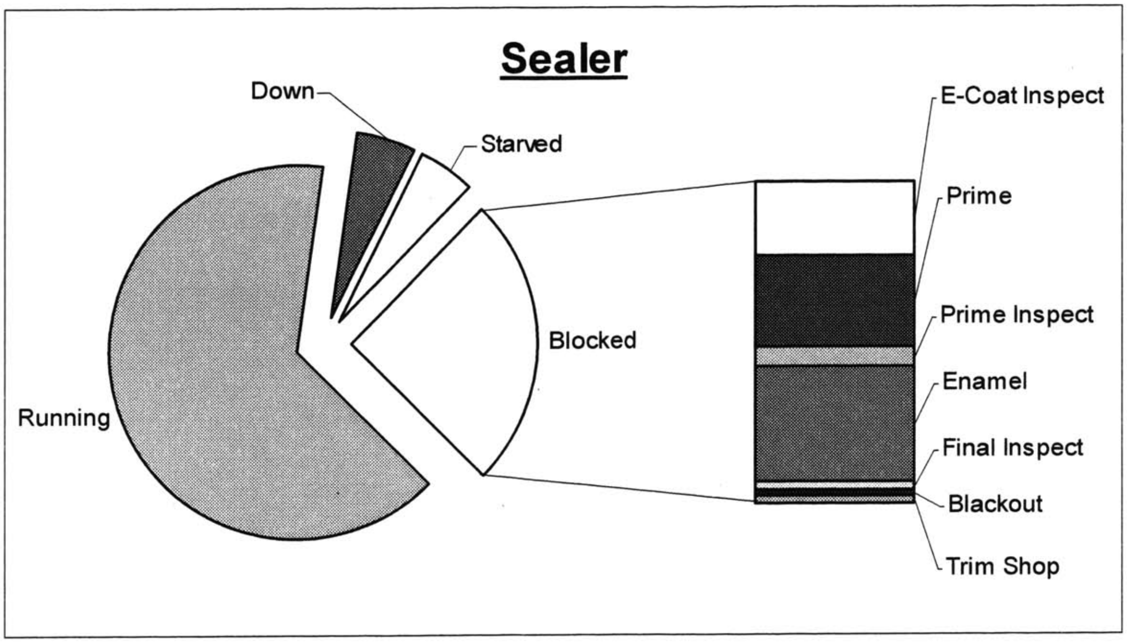

Figure 3.4 Cassidy Shift Report

Next, Sealer blocked time is allocated to the next process upstream, the Blackout process. The formula for determining this value is:

> Sealer_Blocked(Blackout) = Min (Final Inspect_Blocked, Enamel_Blocked, Prime Inspect_Blocked, Prime_Blocked, E-Coat Inspect_Blocked, Sealer_Blocked) – Sealer_Blocked(Trim Shop)

Since Sealer blocked time was already allocated to the Trim Shop, this time is subtracted from the minimum of the blockage observed at all other processes between Blackout and Sealer. Similarly, Sealer blocked time allocated to the Final Inspect process is calculated:

> Sealer_Blocked(Final Inspect) = Min (Enamel_Blocked, Prime Inspect_Blocked, Prime_Blocked, E-Coat Inspect_Blocked, Sealer_Blocked) – Sealer_Blocked(Trim Shop) – Sealer_Blocked(Blackout)

Sealer blocked time should continue to be allocated to successive processes, moving upstream toward the gross constraint, until all of the Sealer blocked time is allocated.

If starved time needs to be allocated, the same methodology applies, but one would begin at the process farthest upstream from the gross constraint, and successively assign the starved time to each process moving toward the gross constraint.

This bottleneck analysis approach has some distinct advantages over other methods. The relative contribution of each process to total throughput loss is calculated, similar to the results given by C-More, but it is done with far less data than the C-More approach. Detailed OEE data, including downtime, quality, blocked, and starved time, need only be taken at the gross constraint (Sealer). At other processes, the only data required is the blocked time (if downstream of the gross constraint) or starved time (if upstream of the constraint). It is not necessary to know the uptime or quality, the size of the buffers between processes, or even the gross capacity of processes besides the gross constraint. This method can be very useful when more complex analytical tools are not available.

There are some limitations. First, this approach does not calculate the actual throughput of the system, and therefore is not capable of modeling improvement scenarios. The method uses actual data, so one must first make process improvements, then observe the effect on gross constraint OEE and total throughput. This may cause some frustration when making improvements, since blocked time assigned to one process may be partially replaced with blocked time assigned to a second process further downstream, once the first process is improved. For example in this case, improvements to the Prime process may decrease the amount of time that Sealer is blocked because of Prime, but part of this reduction may be replaced with additional blocked time allocated to Enamel. One cannot predict in advance each area that improvements will need to be made in order to achieve system throughput targets.

Another limitation is that this method can only analyze data over a time period where blocks and starves flow upstream or downstream, respectively. The purpose of Cassidy's model was to produce a shift report (Cassidy, 1999, p. 62). In many manufacturing plants, including the Ford paint shop, if one process finishes the shift with significantly less throughput than others, managers will continue to run that process on overtime, in order to rebalance the levels of the buffers between processes. If this is the case, then the performance during successive shifts is decoupled, and Cassidy's method can only be used to analyze the data on a single shift. One must look for a consistent pattern to emerge from shift to shift, regarding the allocation of throughput loss, in order to effectively direct improvement efforts to appropriate areas.

This method is only appropriate in processes with little or no scrap. Units exiting the flow as scrap cause a loss in throughput, but will not result in blockage of upstream processes. If there is significant scrap exiting the system downstream of the gross constraint, the results of this approach will be inaccurate. In this case, it may be possible to perform the analysis at the process with the lowest (gross capacity x yield), instead of at the gross capacity constraint.

3.1.6 Simulation

The ultimate throughput analysis method is discrete-event simulation. Using a simulation software platform such as Witness, Automod, Taylor, or ProcessModel, one can create a virtual model of part or all of the manufacturing system, and include whatever level of complexity is appropriate to achieve the desired results. A simulation will typically determine the net throughput of the system, as well as the utilization and reasons for non-utilization of each process. More detailed outputs can be measured, including throughput variability, throughput time, and work-in-process inventory. Multiple part types, reentrant flow, conveyor cycle times, and different production schedules for different processes can all be modeled. A simulation using a commercial software platform also provides the benefit of a visual animation of the process, which can be useful in better understanding and communicating the performance of the system or various improvements.

A simulation model does not necessarily pinpoint the location of bottlenecks. There are two ways to use the model to accomplish this. First, the Flow Monitoring approach can be used with the simulation output blocked and starved data. If one clear primary bottleneck exists, blocked time will transition into starved time at that location in the flow. If this approach is too simple, one must perform the type of iterations done by C-More in its throughput analysis algorithm. The simulation should be run multiple times, each time with one process modeled at

100% uptime and quality, and the other processes modeled at their actual performance rates. The increase in throughput observed in each run should be recorded and ranked, similar to the C-More output. Thus, one can see the contribution of each process to total loss in throughput. These multiple simulation runs can take significant time, depending on the complexity of the model.

3.1.7 Evaluation and Comparison

In a practical scenario where one is tasked with analyzing and improving throughput, the choice of analysis method will be inevitably limited by the data, software, and expertise that is available. The primary concern is that one have a structured approach to identifying throughput bottlenecks that everyone involved in process improvement activities can agree upon. Longcore (1999, p. 69) noted:

> The benefit provided by a structured bottleneck identification process is an enhanced alignment of the improvement team. In earlier improvement efforts, the team frequently spent many meetings arguing over the true location of the bottleneck. Without a structured process, bottleneck identification was subject to personal bias. The failure to reach an agreement on the bottleneck location diluted team efforts as each member focused his or her efforts in the individually identified bottleneck. A structured identification process allows the team to first agree on the process, and then commit to addressing the bottlenecks identified by the process. Through this procedure, the team quickly reaches agreement on the most important improvement efforts.

Beyond this, it is necessary to evaluate the strengths and weaknesses of each of these methods with regard to the particular system. The various methods can be categorized as either data-based (Flow Monitoring, Cassidy Approach), mathematical-based (Gershwin Method, C-More), or simulation-based. Ford's Capacity Analysis Procedure is not considered, since it is inaccurate for most manufacturing systems.

Data-based methods can be very useful in a situation where mathematical or simulation tools are not available (or the expertise to use them is not available). Many manufacturing plants do not have access to these tools, but do have historical data regarding process performance. The Cassidy approach is the more useful of these methods, since it identifies multiple bottlenecks and gives a clear and concise result, but the Flow Monitoring method may be a better way to identify the primary bottleneck over a long time period. These methods cannot be used to investigate throughput improvement scenarios, however, and so one must rely on making improvements without a defined plan of exactly what is required to achieve system targets, and without knowing the precise impact of a process improvement until after the fact.

Mathematical approaches can give detailed results for total system throughput, rank the process bottlenecks, quantify the throughput loss due to each process, and analyze throughput improvement scenarios. Additionally, these results can be achieved in much less time than it would take to run even one computer simulation, much less multiple computer simulations. There are two primary drawbacks to this method. First, there is a limited amount of complexity that can be examined, specifically multiple part types, reentrant flow, and different production schedules for different processes. Second, the mathematical approach may be not be understood by those involved in throughput improvement, and therefore may not be trusted. Loncore (1999, p. 67) noted with regard to the use of C-More:

> Acceptance of the bottleneck identification process is slowed by the complexity of the analysis tool. The mathematics behind C-More are not trivial to explain or understand. Because the method of operation of the tool is not understood, the results are distrusted, at least initially. In addition, the tool cannot model every aspect of the actual system. This allows those who distrust the model to claim that the model is incomplete, and therefore inaccurate.

If these two obstacles can be overcome, there still remains the problem of how to acquire the tool. C-More is proprietary General Motors software, and while the basics of Gershwin's analytics are described in Gershwin (1994), there is no known commercially-available software package that uses this method.

Alternatively, simulation tools are more readily available, although the expertise to make use of them may not exist among engineering personnel in a manufacturing plant. There are many contract vendors that can be used to perform simulation analysis. The main advantage of a simulation is that it is very flexible, can handle whatever level of complexity is desired, and is usually easier for decision-makers to understand (Flinchbaugh, 1998, p. 62). The graphical animation provides an added benefit in helping to understand the operation of the manufacturing system. The primary drawback is the amount of time it takes to build and iteratively run a simulation model of significant complexity.

3.1.8 Bottleneck Analysis Approach Used at Ford

Two throughput and bottleneck analysis tools were used in the Ford paint shop, the Cassidy Approach and discrete-event simulation. Initially, the Cassidy Approach was used to develop a general idea of where improvement efforts should be concentrated. Data collection was already in place at the gross capacity constraint, but blocked and starved data from other processes was spotty. Nonetheless, several process improvements were made based on this analysis that did result in overall throughput improvement.

Simulation was utilized once it became necessary to determine the impact of process buffers in certain areas, to consider various levels of complexity that affected the system, and to model major revisions to the material flow in the process. The simulation model was developed by an outside vendor, using Automod simulation software. A baseline model already existed from the launch of the paint shop several years earlier, so it was not difficult to update the model to current conditions. In order to make the model usable by the plant manufacturing engineers (who had no simulation training), the model was built to run via a Microsoft Excel interface. This interface contained all relevant process parameters such as gross capacities, uptime, quality rates, conveyor speeds, model mix, and production schedules. This allowed simulation iterations to be conducted by the manufacturing engineers as the need arose. Use of the model by those actually working with the process was key to ensuring that the simulation was used on a regular basis when improvement efforts or changes were being considered.

Ford did not have access to a mathematical-based throughput tool, although this would have been useful in analyzing a particular part of the system that was a source of throughput problems. This area was analyzed using the simulation model.

3.2 Improving Throughput

Once the bottleneck locations are identified, there are generally three means to improve throughput at a manufacturing process: increasing performance (uptime, quality), decreasing cycle time, and increasing buffer sizes between processes. These three are not necessarily interchangeable. All three methods were used in the Ford paint shop, in the various areas where they were appropriate.

Increasing performance is the "lean" approach, and will always result in increased overall throughput when done at a bottleneck. This was done at each of the largest contributors to throughput loss.

A decrease in cycle time was performed at the gross capacity constraint, since the existing process capacity would have required over 98% OEE to achieve system throughput targets. However, in some areas the process cycle time was increased in order to improve performance. These were areas where manual stations existed on a conveyor line. The manual operators stopped the line conveyor when their cycle time was greater than the line cycle time. Time was wasted when the operator had to walk to a stop button to stop the conveyor, walk back and finish the job, walk back to the stop button to restart the conveyor, and then walk back to start the next job. Increasing the conveyor cycle time to match the operator's cycle time resulted in smoother flow and a net increase in throughput.

The buffer size between processes was increased in one area, and decreased in another (some of the same conveyors were used, but the flow was rerouted). The total work-in-process in the buffers was not increased, but the buffers were better optimized to achieve greater throughput.

A cautionary note is in order regarding increasing buffer sizes. This method can be very appealing to management in a manufacturing plant, since it has the potential to improve throughput simply by spending money on additional conveyors, storage banks, etc. No process engineering knowledge is required to improve the performance of machines, and no knowledge of manual operations is required to reduce operator line stops or reduce cycle time. There are two potential problems with this approach. First, increasing buffer sizes results in diminishing returns in throughput improvement as the buffers get larger. Increasing buffer sizes as a solution to inadequate throughput may distract the focus from process improvement, and the real problems may not be addressed. Additionally, real process problems may continue to grow, since little focus is being put on them.

The second problem is that an increase in buffer size may not result in increased throughput. Buffers exist to absorb the variation in throughput between sequential processes. However, this assumes that the average throughput rate at each process is the same. If one process is appreciably slower than others in the system (i.e. a bottleneck), then a larger buffer will just fill up or empty out and stay that way. Increased buffer sizes can help if there is a desire to run one process on a different production schedule than another (through breaks, etc.) by decoupling areas that are running on different schedules.

3.3 Performance Measurement Tools

Several tools were put in place at the Ford paint shop to aid in throughput analysis, bottleneck identification, and throughput improvement. These tools were essentially computerized data tracking systems, integrating data from process Programmable Logic Controllers (PLC's) and barcode scanners that tracked the movement of each truck through the paint shop.

The most important of these was an automated data collection system for tracking process performance. A database was constructed that recorded a simplified set of faults from each process PLC. If an operator stopped a process manually, the operator station, time, and duration of the stop were recorded. If a machine or robot faulted and caused the process to stop, a separate entry was made recording its time and duration. Special PLC faults were programmed to identify a blocked or starved condition, and these faults were also logged in the database. Quality rates were also tracked. Each shift, a summary report was produced showing the lost production time at each process, and the resultant OEE of that process. This system collected excellent, accurate data for use in both the Casssidy Approach and the paint shop simulation.

The trucks in the paint shop each had designated parameters relating to their paint color, style, routing, etc. As such, it was necessary to track each cab and box with a barcode that was imprinted on its metal skid. Barcode readers were placed throughout the plant, to track the movement of units from one process to the next. A useful by-product of this system was that the time between successive units entering a process could be measured. The system was programmed to only record measurements within a pre-defined range, thus minimizing the effect of process downtime on this measurement. The result was an approximate measure of actual gross cycle time, from which actual gross capacity could be determined. This measurement was used in the automated calculation of OEE, and was also used to compare to the planned design cycle time of the process, to determine if another factor (such as the transfer automation or slow line speed) was causing the process to be fed at less than its designed rate.

Since the barcode scanners tracked the style of each unit and its path through the paint shop, it was also possible to track units with quality problems and categorize them by model, paint style, number of paint coats, etc. This information was extremely valuable in identifying the largest contributors to quality problems, so resources could be assigned to fixing them. The quality of cabs vs. boxes was measured, as well as monotones vs. tutones, and repaired units vs. first-run units.

Good data and quick feedback of the data was essential in all steps of the throughput improvement process. In many systems, it may be more valuable to begin by establishing a solid data-collection system, rather than jumping into throughput improvement efforts. In a lean system, process improvement is an ongoing effort, and a performance measurement system is key to enabling this to occur on an ongoing basis.

Chapter 4: Manufacturing System Design for Throughput

This chapter presents a template for the design of a manufacturing system with respect to throughput, with the highest-level goal being to produce to takt time. The design details numerous reasons for throughput loss and the means to prevent them, and describes the metrics that are used to monitor and control the system at each level.

The design parameters are presented using axiomatic design and design decomposition framework, building on the axiomatic design and design decomposition methodology of Nam P. Suh and performance measurement relationship to axiomatic design developed by David Cochran. Both Cochran and Suh are MIT professors of Mechanical Engineering. The design presented is adapted from the research done by Cochran and the Production System Design Laboratory on the Manufacturing System Design Decomposition.

While Cochran's design applies to the entire manufacturing system, this one will focus solely on throughput issues. In addition, this design was developed to apply to processes like those observed in the Ford paint shop. Key characteristics of those processes are:

- Units are processed sequentially through a production line on a moving conveyor.
- Operators or automation performs operations on the unit, either while the unit is traveling past the station, or stopped temporarily on the conveyor.
- Operators and automation both have the ability to stop the production line at any time.
- Multiple product styles are produced on the same line, and the operation cycle times vary from style to style.
- Multiple products can be produced in any sequence, with no setup time between product variants
- Processes are connected to each other via material handling automation.

The applicability of this design to other types of manufacturing systems has not been investigated.

This approach was used in the Ford KTP Paint department during the internship project, to develop a measurement hierarchy and pinpoint the specific, detailed causes of throughput loss within the system (once the bottleneck processes were determined). In the case specific to Ford, an additional throughput loss factor was added to deal with product mix variation from the standard or norm. Varying numbers of tutone units, trucks with boxes, and cab styles affected throughput by using more or less capacity than the expected mix. This is not included in the model shown here, in order to make the model generally applicable to other manufacturing systems.

4.1 Axiomatic Design and Design Decomposition

Axiomatic Design is a design methodology for developing solutions in the form of products, processes or systems that satisfy customer needs through a logical mapping framework (Stec, 1998, p.37)[6]. MIT professor Nam P Suh developed the methodology in the late 1970's. It is called axiomatic design because it is based on two axioms or fundamental truths:

1. The Independence Axiom – Maintain the independence of Functional Requirements.
2. The Information Axiom – Minimize the information content.

4.1.1 FRs and DPs

The approach provides a scientific basis for design in which the "Customer Wants" are translated into "Functional Requirements" (FRs). FRs represent what you want the system to do, or what you want to accomplish. The goal of axiomatic design is to satisfy each FR with a distinct "Design Parameter" (DP), which represents how you accomplish the objective. The proper selection of one DP for each FR will satisfy the Independence Axiom, in that each FR will be achieved independently. Suh (1990) states that the mapping process is not unique, meaning that more than one set of DPs can be generated that satisfy the FRs.

4.1.2 Coupling

While one DP is defined for each FR in the design, it is possible that a DP created to satisfy one FR might also have a positive or negative affect on another FR. This is referred to as

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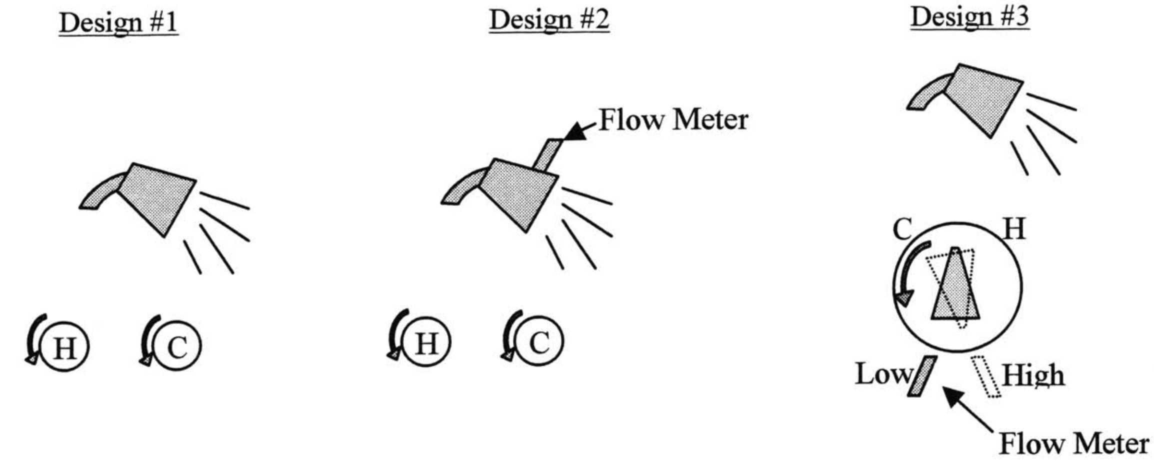
[6] Much of the summary of axiomatic design is adapted from Stec (1998).

"coupling." A design can be uncoupled, in which each DP affects only its own FR, partially coupled, in which only some DPs affect more than one FR, or fully coupled, in which all DPs affect all FRs. Coupled designs are typically considered undesirable.

Customer Want: Controllable running water

FR1: Control water temperature
FR2: Control water flow rate



DP1: Hot & Cold Valves
DP2: Hot & Cold Valves

$$\begin{array}{cc} & DP \\ FR & \begin{bmatrix} X & X \\ X & X \end{bmatrix} \end{array}$$ *Fully Coupled*

DP1: Hot & Cold Valves
DP2: Flow Meter

$$\begin{array}{cc} & DP \\ FR & \begin{bmatrix} X & -- \\ X & X \end{bmatrix} \end{array}$$ *Partially Coupled*

DP1: Mixing Valve
DP2: Flow Meter

$$\begin{array}{cc} & DP \\ FR & \begin{bmatrix} X & -- \\ -- & X \end{bmatrix} \end{array}$$ *Fully Decoupled*

Figure 4.1 Axiomatic Design of a Shower Faucet

A classic example that describes axiomatic design and the concept of coupling is the design of a water faucet. A shower faucet is shown in Figure 4.1. First the Customer Want, controllable running water, is translated into two functional requirements for the design: control of water temperature and control of water flow rate. Then a DP is established for each of the FRs. Three different sets of DPs are shown. The first design uses the hot and cold water valves as the DP to accomplish both FRs. This design is considered coupled. It is extremely difficult to achieve both functional requirements with this design. The two valves could be set to achieve the correct temperature or the correct flow, but achieving both would require numerous iterations of trial and error, or an extremely detailed knowledge of the valve design and flow characteristics. Coupled designs usually require iteration to achieve their FRs, if they can achieve them at all.

The second design uses the hot and cold water valves as the DP to establish the temperature, but uses a flow meter on the showerhead to establish the flow rate. This design is partially coupled. The hot and cold valves will affect both the temperature and the flow, and the flow meter affects only the flow. A partially coupled design can still achieve the FRs independently, as long as the FR-DP matrix can be arranged to be triangular, and the DPs that affect the most FRs are set before the other DPs. In this case, the solution is to adjust the hot and cold valves to achieve the correct temperature setting, and then adjust the flow meter to achieve the desired flow rate.

The third design uses a mixing valve to set the temperature of the water, and a flow meter to control the flow rate. This design is fully decoupled. Each DP affects only its own FR, and the FR-DP matrix is diagonal. The temperature and flow can each be set independently, without affecting the other. This design is considered to be the best, since it is most easily able to achieve its functional requirements.

4.1.3 Design Decomposition

Axiomatic Design involves a process of hierarchical decomposition that allows the designer to examine small parts of a larger problem (Stec, 1998, p.38). The process begins with defining the high-level FRs, defining DPs for each of those FRs, then breaking the FRs down into component FRs that must be achieved to meet each high-level FR. Figure 4.2 shows a typical decomposition tree. Each FR has its own DP, which must be determined before the next level of decomposition, in order to assess the amount of coupling at each level. The elements at each level are then typically arranged so that the DPs that are coupled to the most FRs are positioned on the left side of the tree, indicating that they are to be established first in the design.

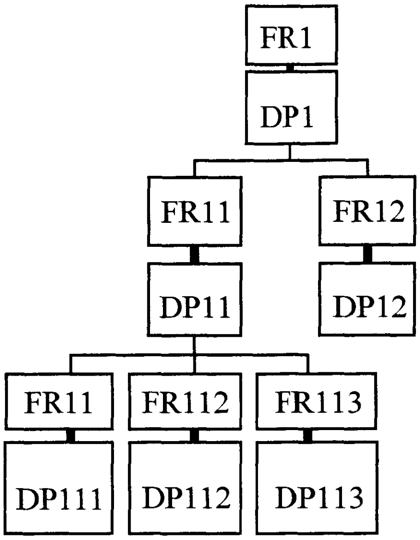


Figure 4.2 Hierarchical Design Decomposition

4.2 Multi-Level Performance Metrics

Many studies have been done on choosing good performance measurements, and there is not always a consensus among different researchers or different firms (Kowalski, 1996, p.35). More on this subject is presented in Chapter 5, but some is relevant to the design decomposition. The main theme developed in Kowalski is that measurables should be used that correspond with the design parameters that accomplish each functional requirements of the system. When the measurables match, it is easy to see if each of the requirements is being achieved and exactly where problems exist.

This means that different, more specific metrics will be used at lower levels of decomposition than at the high levels. Thor's method brings up the same points, that organizations need overall strategic measures but also need local measures that can be directly affected by people doing the actual work, and that the firm should be thought of as a hierarchy where each level receives the measurement feedback needed for that level of control (Thor, 1993). Arnow similarly stresses the need for metrics to align authority with responsibility, as a good metric holds people accountable for their own actions, not those of others (Arnow, 1993, p.51-52). This design presents throughput metrics that are useful at each level, and while a metrics is not established for every design parameter, the level of aggregation is kept to the minimum that is necessary to make the tracking of measurements practical in a real manufacturing plant. More specific metrics for each FR can be monitored in a plant if there is an indication of a potential problem in this area.

This design decomposition will present the measurables that can be used at each level to control the system, and Chapter 5 will discuss further how those measurables should be used and communicated in the organization. Thor's hierarchical distinction will be followed, which categorizes the levels as follows:

> Level I – Manufacturing Process Level – Control and improvement decisions made on the plant floor by operators, team leaders, or first-line supervisors
>
> Level II – Analysis Level – Measurement of the achievement of business goals, where decisions are made by engineering, maintenance, or middle management
>
> Level III – Production System Design Level – High-level management makes decisions regarding the structure or design of all elements and changes in resources.

Since the decomposition typically proceeds from top down, Level III will be discussed first.

4.3 Level III Decomposition – Production System Design Level

Cochran's Manufacturing System Design Decomposition begins to define the functional requirements at the top of the business. The first requirement is to maximize long-term return on investment. Since this project dealt specifically with throughput, it will start at a lower level, with the first functional requirement as "Produce a customer-defined product mix at takt time". Other requirements are essential to achieving the return on investment FR, such as quality, lead time reduction, direct and indirect costs, but this design will focus solely on the issues that affect throughput.

As shown in Figure 4.3, the DP for FR1 is to consciously design the system for takt time production. This means two things as the design is decomposed, that the amount of lost throughput should be minimized, and that the lost throughput should somehow be overcome. The DP to overcome the lost throughput is process overspeed. This means that each process in the system will be designed to produce at a rate that is faster than takt time, in order to make up for whatever lost production occurs. This is a typical approach to system design in an automotive plant. The amount of overspeed designed into a process typically increases with the variability of a process, and its distance upstream from the end of the production line.

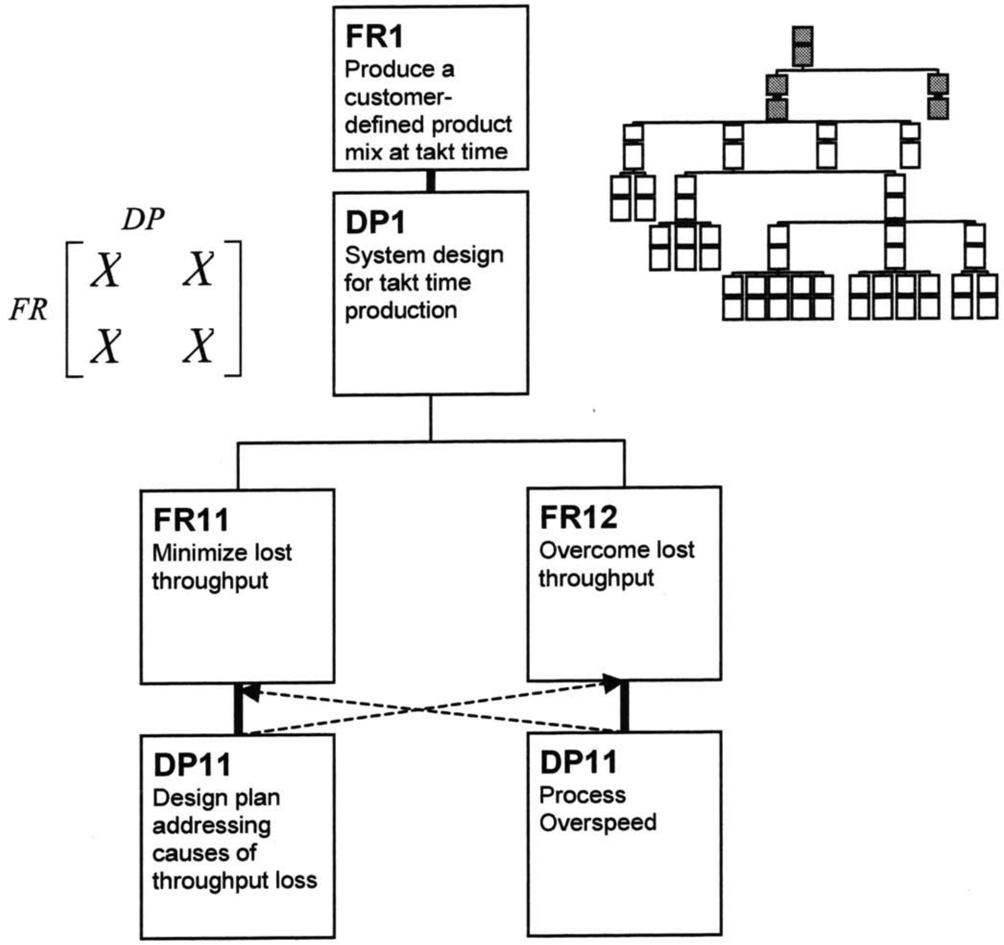


Figure 4.3 Level III Decomposition

Note that even at this high level, the design is fully coupled. The coupling from DP11 to FR12 has a positive relationship, in that a reduction of lost throughput increases the ability to overcome that lost throughput. However, the coupling from DP12 to FR11 is negative. Increased process overspeed can result in more throughput loss, by increasing the probability of defects and increasing the chance of operator or automation line stops due to cycle time. Therefore, the net affect on throughput of increasing the amount of overspeed is unclear. While a coupled design is typically undesirable, there is little alternative in this case. Other means of overcoming throughput loss, such as running individual processes overtime or through breaks, will still result in coupling due to increased interactions (blocks and starves) between processes that are on different schedules, in addition to being very costly to the plant.

Although the design is less than ideal, some lessons can be gained from it. First, process overspeed should be kept to the minimum that is necessary to overcome throughput losses. Running a process faster, simply for safety's sake, is not optimal and could be causing problems that would not otherwise exist. Second, one must not blindly depend on process overspeed to overcome throughput loss, without a solid understanding of the causes of that throughput loss. If the causes are related to operator or automation cycle time, such as an improper line balance, insufficiently designed automation, or overwhelming product mix variation, or if the cause is slow material handling equipment or even process interactions, then increased process overspeed is likely to accomplish nothing or cause a net decrease in throughput. Third, if process overspeed is to be increased from an existing level, the process should be studied to ensure that the increased speed would not result in worse quality, more downtime, more interactions, etc. Additionally, the material handling equipment should be studied to determine if it needs to be sped up as well.

Performance measures for Level III are typically used by management and system designers, and should include the aggregated effect of all the lower level causes of throughput loss. For FR1, most manufacturing plants would either measure the actual production takt or the actual jobs per hour produced by the system. FR11 is where the aggregated measure of OEE is most useful, and FR12 should provide a constant measure of the % process overspeed.

FR1 – Actual takt OR actual jobs per hour

FR11 – Overall Equipment Effectiveness
FR12 – % Overspeed (customer takt time / process cycle time)

The detailed reasons for throughput loss are shown in the decomposition of FR11, which begins Level II in the next section.

4.4 Level II Decomposition – Analysis Level

4.4.1 Throughput Loss Components

There are four primary causes of lost throughput in a system like that in the Ford paint shop. Production is lost due to quality, when units must be scrapped or rerun. Process downtime or disruptions causes losses since the process is not running. In the paint shop, units are transferred from one process to another via material handling conveyors. Throughput can be lost if the cycle time of these conveyors is greater than that of either of the surrounding processes, meaning that parts don't get pulled from or fed to the processes as fast as necessary. Lastly, the processes can interact, blocking and starving each other. The four FRs of this level of the design state the goal of minimizing each of these loss components, as shown in Figure 4.4.

For FR111, the DP that should be used to control quality is in-station process control (an element of FPS). ISPC covers many specific actions, including mistake-proofing devices and self-inspection, but also includes what Ford calls the "Stop Button Procedure." Similar to the use of andon cords, this procedure gives each operator the ability to stop the production line under certain conditions. One of these is the detection of a defect, whether created by the operator or by an upstream operation. Because this method is used to control quality, process disruptions are created when poor quality exists. Therefore, coupling is created between this DP and FR112.

DP112 deals with planning during design for the reasons that may lead to process downtime, and will be decomposed in the next section.

FR113 describes the issue with slow cycle time due to material handling. Material handling is not a value-added function in manufacturing, but if it must exist it should absolutely not constrain the level of production in any way. Several of the throughput improvements made in the Ford paint shop dealt with speeding up, reprogramming, or redesigning material handling automation to ensure that it was faster than the surrounding processes, and ensuring that it was faster for all variations of product mix that could be traveling through it at any given time.

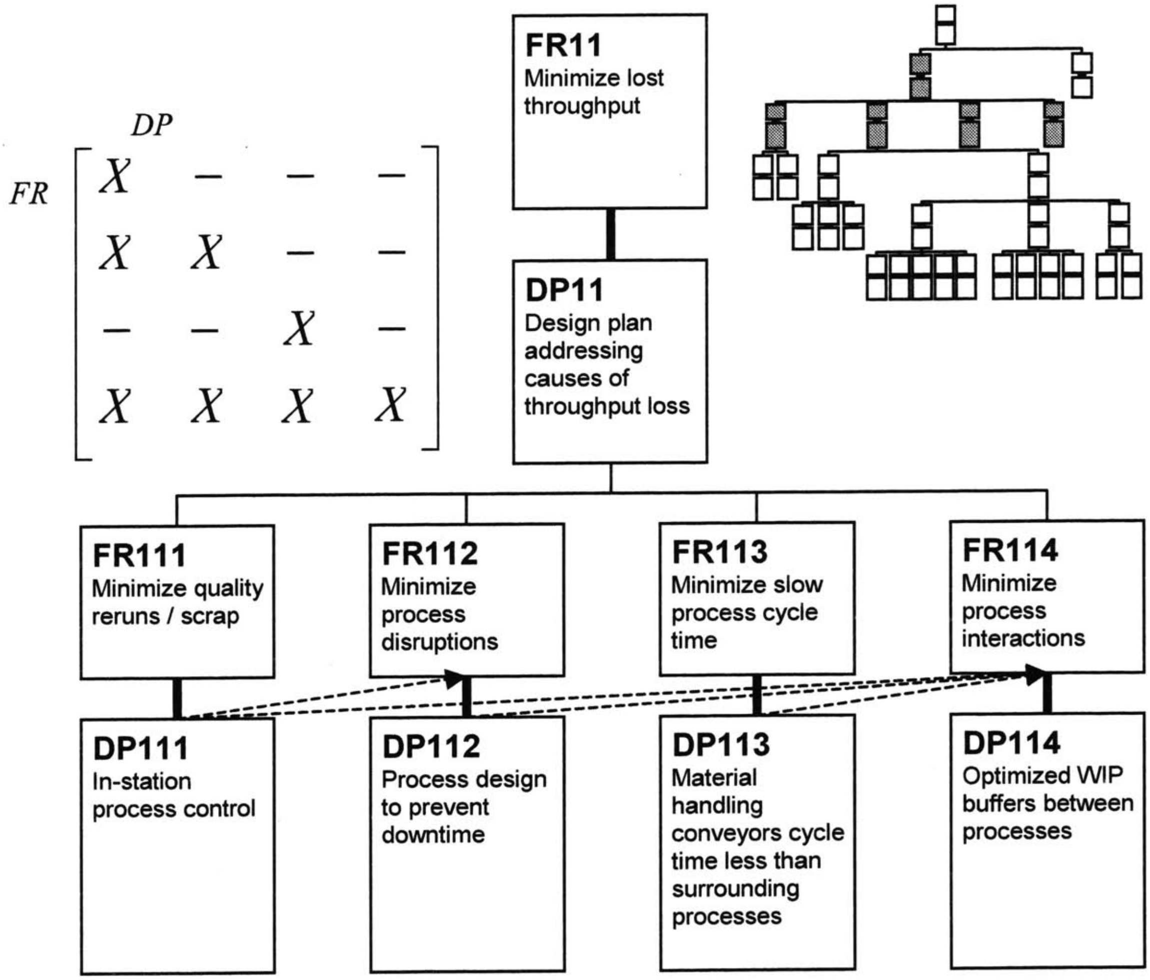


Figure 4.4 Throughput Loss Decomposition

Since all of the first three DPs deal with throughput loss, and thus throughput variability, they are all coupled to the fourth FR dealing with process interactions. Since every process does not produce at takt time every second of the day, flow through the system will inevitably ebb and surge through the system. To absorb this and prevent blocking and starving of the processes, a

DP is defined to allow units to accumulate between processes in WIP buffers. The level of WIP that can accumulate must be optimized, managing an inherent tradeoff between maintaining throughput while not creating excessive lead-time, inventory levels, delays in detecting defects, or lack of visibility of process disruptions.

Care must be taken when using DP114 as a means to increase throughput. While no coupling exists to other FRs, the need for this FR exists only because of the other causes of throughput loss. A better approach is to first address the assignable causes of lost production due to the other three factors, since increasing the buffer size can tend to hide these causes and allow others problems to arise undetected.

This decomposition is part of Level II, the Analysis Level, and thus the performance measures must be designed to provide information to middle management and engineering regarding where to focus improvements and changes to the system. They must also support the bottleneck analysis methods described in Chapter 3. For these FRs, the OEE measure can be used in a greater level of detail than in Level III. It is necessary now to break out the specific causes of why OEE is not 100%[7]. OEE, as currently defined by Ford, includes three components:

Quality % -- % of units rerun or scrapped
Availability % -- process uptime as a % of scheduled time
Performance Efficiency % -- units produced, as a % of maximum possible units, considering losses from Availability and Quality

Quality % is a satisfactory measure for FR111, and Availability % measures what is important for FR112. However, Performance Efficiency in the OEE measure is a catch-all metric that aggregates the effect of all lost production not considered in the first two metrics. This includes blocks and starved time, as well as the effect of slow material handling[8]. In order to be used to control the system, these two factors must be disaggregated into separate measurements. In the Ford paint shop, and at KTP in general, both Blocked % and Starved % were broken out

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[7] Not that 100% is necessarily the goal. The desired level of OEE is that at which the process can produce at takt time. The proximity of this target to 100% will depend upon the level of process overspeed.

[8] In a real measurement environment, Performance Efficiency also includes the effect of inaccurate data, unrecorded downtime, etc.

into separate measurements, leaving Performance Efficiency % to cover only the effect of material handling[9]. The result is a utilization graph similar to that shown in Figure 4.5.

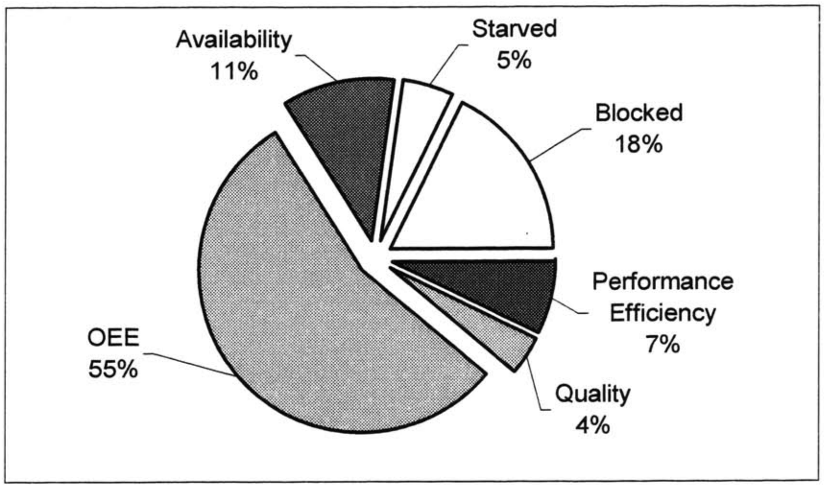

Figure 4.5 OEE and Throughput Loss Components

While OEE is a coupled measurement, decomposing it in this way allows one to measure the achievement of the functional requirements in Level II, while at the same time relating those measurements to the higher-level OEE metric in Level III. This philosophy of measurement remains consistent throughout this design. Measurements are taken at the level of detail needed to determine whether the functional requirements are achieved, but it is clear how those measurements relate to the higher-level requirements of the system.

4.4.2 Process Disruptions

The decomposition of FR112 includes the two types of process disruptions observed in the paint process: operator line stops and automation line stops. These two will each be expanded later in the Level I decomposition.

This level is included in Level II, since it is still critical from an analysis standpoint to understand whether throughput losses from process disruptions are coming from manual or

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[9] In the design decomposition, minimizing blocked time and minimizing starved time could be described as two separate FRs, or as decomposed FRs under FR114, thereby maintaining one metric for each FR. That level of detail is unnecessary for this design.

automated stations. These two classes of problems require different types of resources and different types of problem solving to correct them.

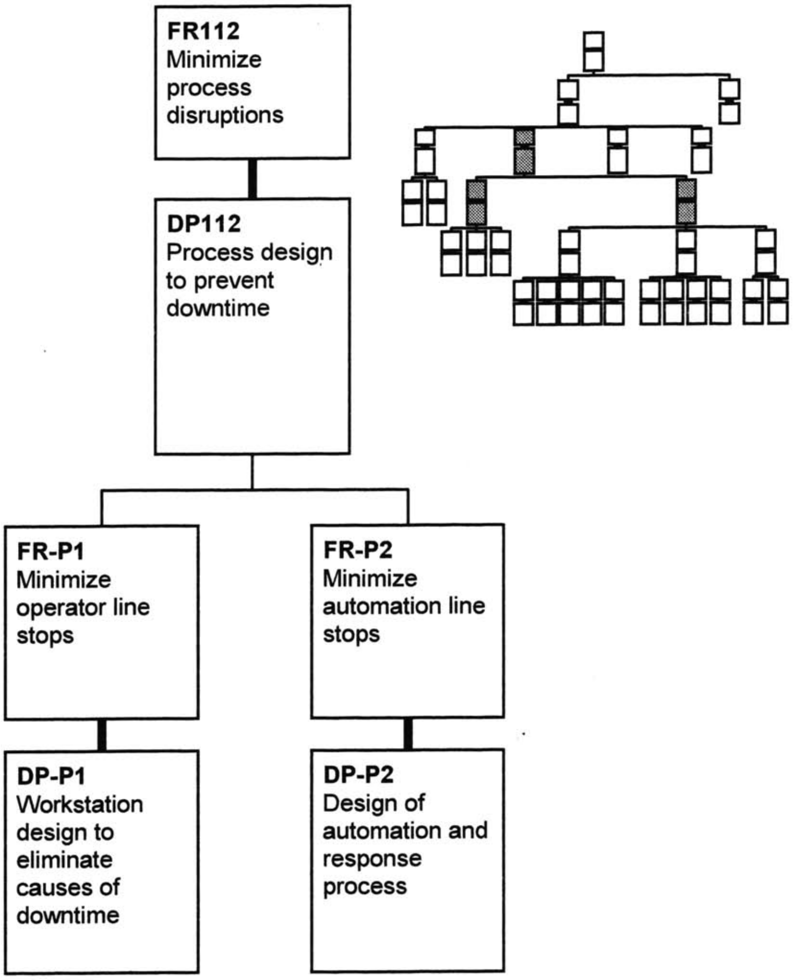

Figure 4.6 Process Disruption Decomposition

In terms of measurements, these two FRs could be considered subsets of the "Availability" metric defined in the last section. However, at some level in the decomposition it becomes infeasible to continue to break OEE down into more and more categories. This level is better served by measuring the actual time that each process is down each shift. Both the actual shift-by-shift data and the weekly average are useful for control purposes, so one can interpret both the mean and variance of the data. At this point it also becomes appropriate to break down the data separately for each work crew[10]. At KTP, different operators, skilled trades, supervisors, and engineers worked on each work crew. It was necessary to break down this data in order to make it relevant to the people in the system.

Level II is where the effect of average product mix variation was added to the decomposition. While it is important to understand the effect of this variation, it is not usually something that can be eliminated or even affected, but rather should be anticipated and designed for if necessary.

4.5 Level I Decomposition – Manufacturing Process Level

Level I contains the individual issues that affect throughput on the shop floor from day-to-day, hour-to-hour. These FRs and DPs become more detailed, and apply more specifically to the processes be analyzed. Accordingly, the measurements become more detailed too. It becomes more difficult to match a measurement to each FR-DP pair, and for practical purposes no attempt will be made to do so. At this level, a somewhat aggregated measurement can help point to the location of problems, after which more detailed analysis or measurements could be performed to help identify the exact problem and solution. Information at this level is most appropriate for the production work teams, machine operators, and skilled trades.

4.5.1 Quality

Throughput losses due to quality could be decomposed extensively into issues regarding man, machine, method, materials, and Mother Nature, typically referred to as the "Five M's," and is so decomposed in the Manufacturing System Design Decomposition by Cochran. However, for purposes of this design, it will be simplified into two components: initial defect creation and subsequent defect creation. The elimination of initial defects involves identifying and eliminating the causes of variation, through proper training, mistake-proofing designs, and process control and monitoring. The minimization of subsequent defects requires prompt feedback of defect

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[10] The KTP paint shop worked three crews, twelve shifts per week.

creation, through effective use of in-station process control, real-time measurement systems, and the reduction of time delay between the operation and its inspection.

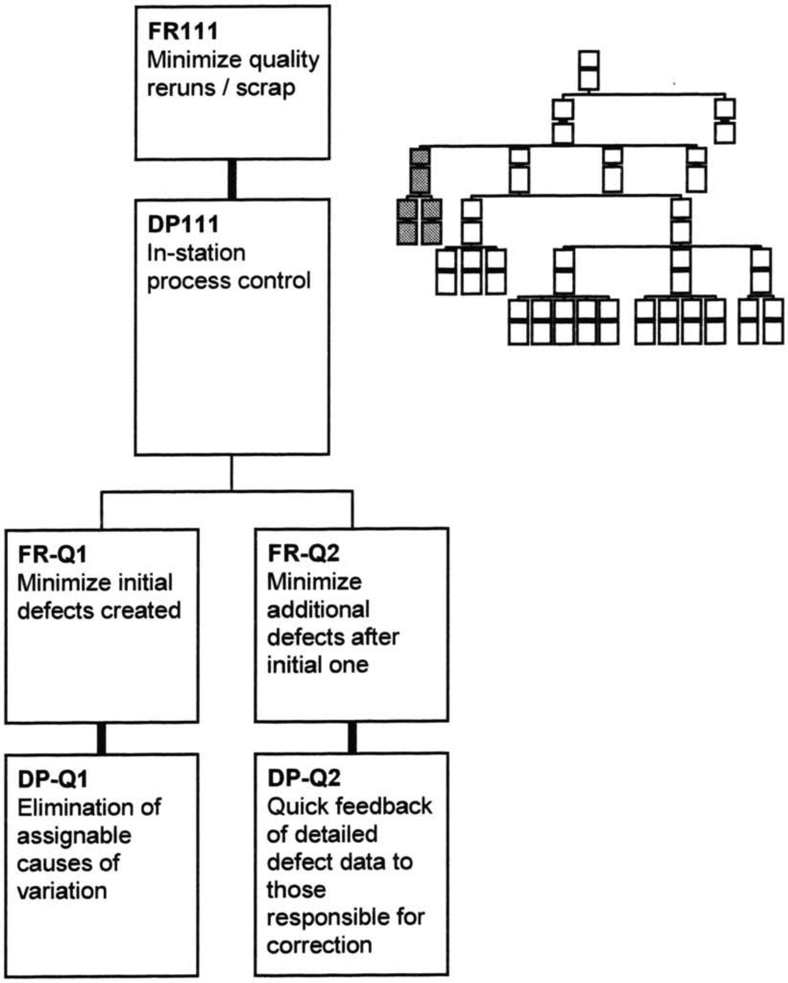

Figure 4.7 Quality Decomposition

It is difficult to define standard measures for this level of the design, short of categorizing defects into each of the five M's, but some general guidelines can be considered. First, the only purpose of measurements at this level is to help control the system, not for reporting purposes. Therefore, the primary concern is that the measures be useful and meaningful to those who are responsible for and capable of eliminating the defects. The measures should consider the desired output of each operation in the process, and track whether that output was achieved. The measurement scheme should be capable of pinpointing not only the type of defect, but point to the specific operation in which it was created. Input variables to the process should be measured in areas where the relationship between inputs and outputs is reasonably known. Additionally, the quality information should be fed back to the actors in the system as quickly as possible, as is the case with all of the Level I measurements. Chapter 5 will further develop the requirements for a quality feedback system that would be useful to operators in the paint process.

4.5.2 Operator Line Stops

Moving back under the "Process Disruption" branch, Level I continues with the decomposition of operator line stops. There are primarily three reasons why an operator would need to stop the production line in a process like that in the paint shop. First, the average cycle time of the manual operation might exceed the average cycle time of the production line. Elimination of this type of line stop is essential, since it is fully preventable and can create major problems (even quality problems) when not corrected, by causing operators to get out of the rhythm of work. It also causes lower throughput, since stopping and restarting the line takes up time, even if only a few seconds. The solution is a correct balance of work tasks between operators, so the average cycle time of each operator is less than that of the line[11]. Different operators may work at different speeds, which must be considered in the balance. Line balance is often a task that is best left to the work team.

The second cause of operator line stops is also due to cycle time, but not average cycle time. In a process where multiple products have varying work content, they will also have varying cycle time. To prevent waste, it is necessary to balance the line to the average cycle time. However, this means that in any given time period, the mix of product may contain more or less of the heavy-content product types. If too many heavy-content units are processed at once, the operator will fall behind the line cycle time, and eventually stop the line when the end of his or

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[11] Often, union work rules define a maximum percentage of an operator's cycle time to line cycle time, usually around 90-95%.

her workstation area is reached. One way to prevent this in general is to ensure an even, level mix of product. Practically, this is rather difficult in the paint shop since the jobs are sequenced based on optimized criteria for the entire plant, and get rearranged in the paint shop anyway due to the level of reentrant and rework flow in the system. The recommended means to control it here is to design the station to accommodate a random mix of product, assuming a probability for each type as defined by the overall mix ratios.

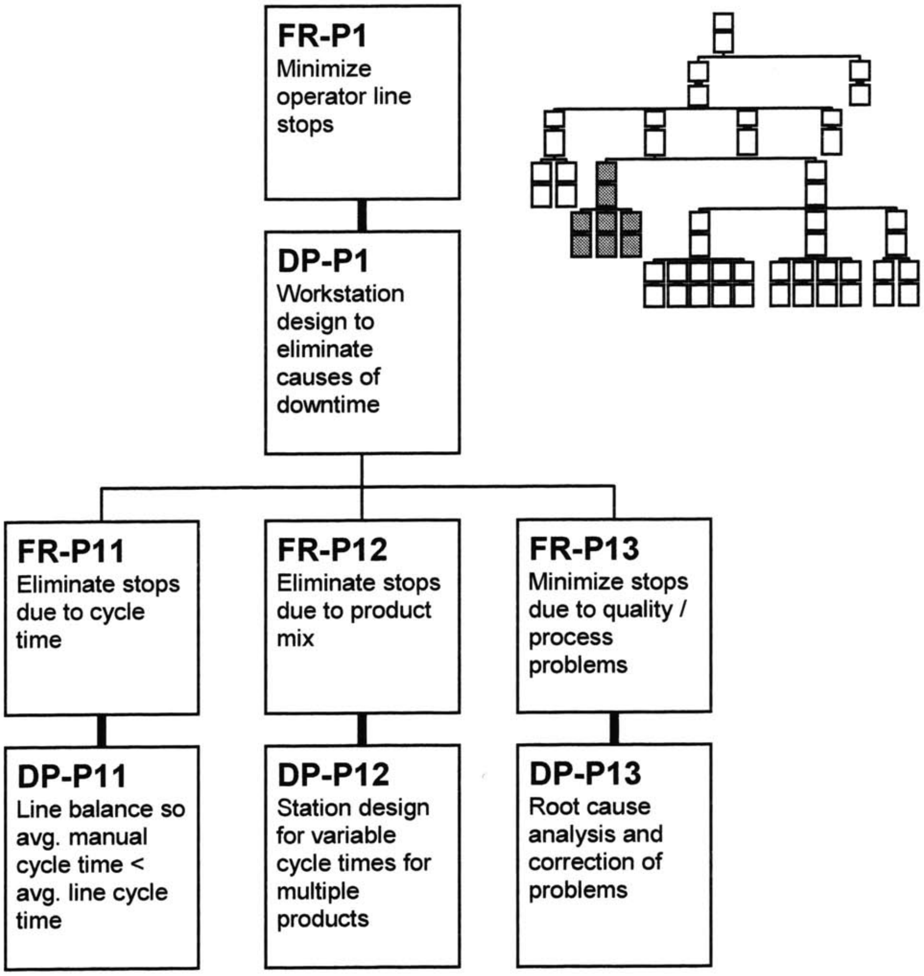


Figure 4.8 Operator Line Stop Decomposition

This could be done one of two ways. On a moving line, it is simply necessary to make the workstation wider than normal, to allow an operator to "go in the hole" when working on the heavy-content units, and then catch up when light-content units arrive. An approximate required width of the station can be determined mathematically using a binomial distribution over multiple trials. The mathematics are not stochastically determinant, since the process is really a random-walk, but a reasonable approximation can be made that will minimize the probability of an operator running out of space. The second way to accommodate variable cycle time is to design a workstation separate from the moving conveyor line where the unit stops, but has small accumulating buffers upstream and downstream from it. When a heavy-content job is in the station, other units can accumulate behind it, which can then be drawn down when light-content units are processed. In this case, the size of the accumulation buffer is the critical parameter instead of the station width. The mathematics for these approaches is developed in Appendix A.

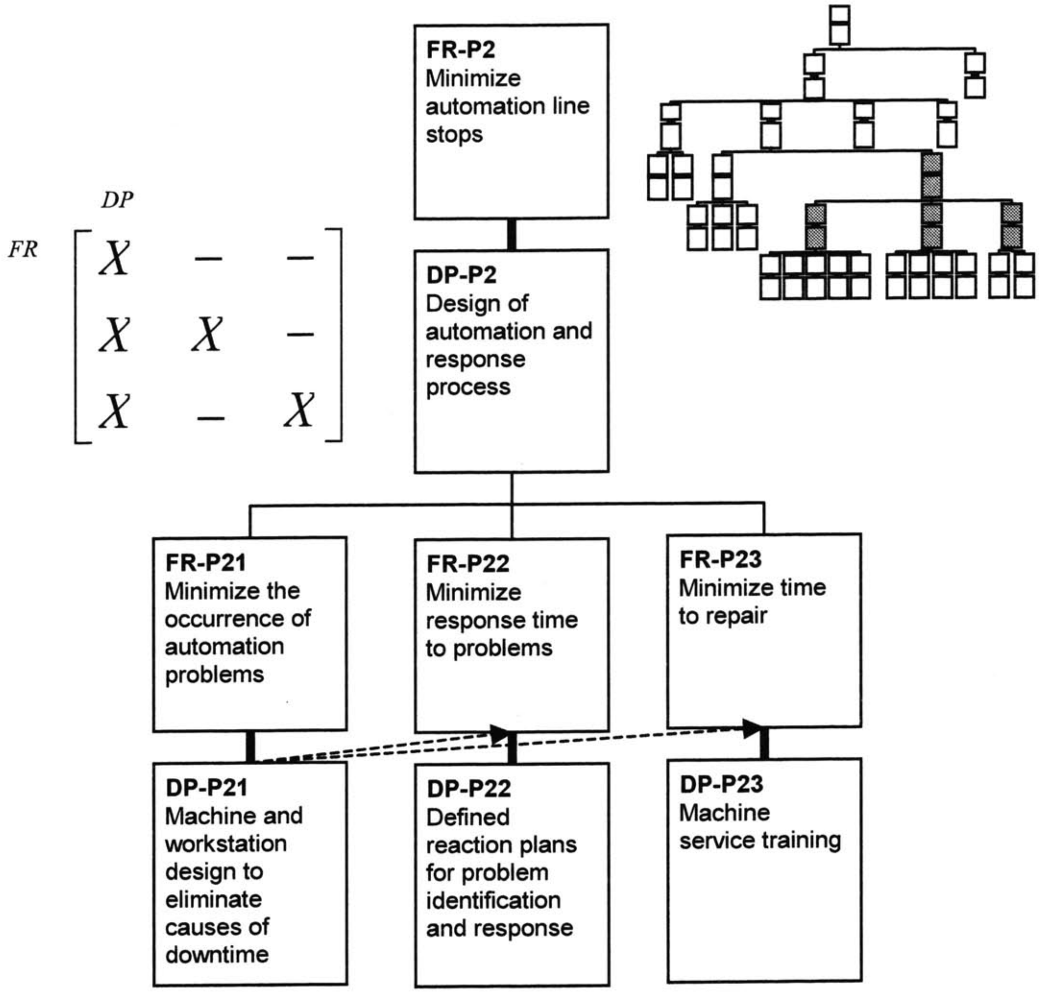
The third reason why an operator might stop the production line is to correct a quality problem with the product, or a process problem such as a broken tool that prevents the creation of a good product. Prevention of these problems requires that the issue be identified when it occurs, and the root cause of the problem be determined and corrected as soon as possible.

There is not really a practical way to measure whether each of these three FRs are being achieved separately, since it would require every operator to record the occurrence and cause of each and every line stop (of which there are hundreds or thousands every shift). The best measure that was found was to break the line stop time down to show how much came from each individual station. If the work team can see that one operation causes significantly more line stop time than any other, it can work to investigate which of these three reasons is the cause. Without an ability to pinpoint line stops to an operation, and track their improvement, it will be difficult for the team to focus their efforts.

4.5.3 Automation Line Stops

Looking at line stops caused by machines or automation requires a greater level of detail, and thus an additional level of decomposition. The first level yields three key requirements that will lead to a minimum of process downtime: minimizing the occurrence of problems, minimizing the response time to problems, and minimizing the time to repair problems.

Both DP-P21 and DP-P22 are coupled to FR-P23. A design that minimizes the occurrence of automation problems will allow repair personnel to respond faster to existing problems, and focus on repairing those problems faster.



$$\begin{array}{cc} & DP \\ FR & \begin{bmatrix} X & - & - \\ X & X & - \\ X & - & X \end{bmatrix} \end{array}$$

Figure 4.9 Automation Line Stop Decomposition

Measures that are useful at this level are overall Mean Time Between Failure and Mean Time To Repair measurements for a specific process or operation. At Ford, the inverse of MTBF was used more frequently, which was the frequency of a problem over a given time interval. "Twelve occurrences per shift" or "three occurrences per hour" seemed to give more meaning to the metric, making it more useful to operators and engineers. These two metrics do not specifically measure the response time to problems separate from their repair time. This would be a very difficult thing to measure, especially with an automated data collection system. Some allowance must be made in this case for those observing the system to exercise personal judgment in determining the level of response time versus repair time.

4.5.4 Automation Problems

Minimization of the occurrence of automation problems required some of the same attention as for manual line stops, but also some others. Similar to manual operators, automation requires a certain amount of time to perform its operation, which may vary for different product styles. Therefore, the design of the workstation must consider the same factors, which are broken out into FR-P211 and FR-P212. The average automation cycle time for all products must be less than the process cycle time, to ensure the automation can process jobs as fast as they are received. Additionally, the workstation should be designed so that the automation can fall behind on high work content jobs and be able to catch up on low work content jobs. As described in section 4.5.2, this can be done either by making the workstation wider than normally required (if the automation is moving with the conveyor line), or by separating the workstation from the moving line and incorporating decoupling buffers upstream and downstream of the station. A mathematical procedure for determining the required parameters is described in Appendix A.

Automation downtime that is not product-related is divided into three categories: common-cause faults, foreseeable machine failures, and unforeseeable machine failures. Common-cause faults occur when a machine stops due to an error in its controller that can be corrected by resetting the fault and restarting the machine. These may cause from 30 seconds to a few minutes of downtime in the process each time they occur. Their root cause is often not known for certain, and since machine operators can fix them, resources are often not immediately assigned to correct them permanently. However, even though each occurrence may only cost a minute of lost production, their continued and repeated occurrence causes a constant drag on process throughput that must be corrected. DP-P213 calls for a concerted effort by cross-functional teams that are assigned to correct problems. Ideally, these are led by skilled trades or engineering personnel. The teams must be cross-functional, since the problems are typically too complicated to be solved by someone with a single-disciplined background.

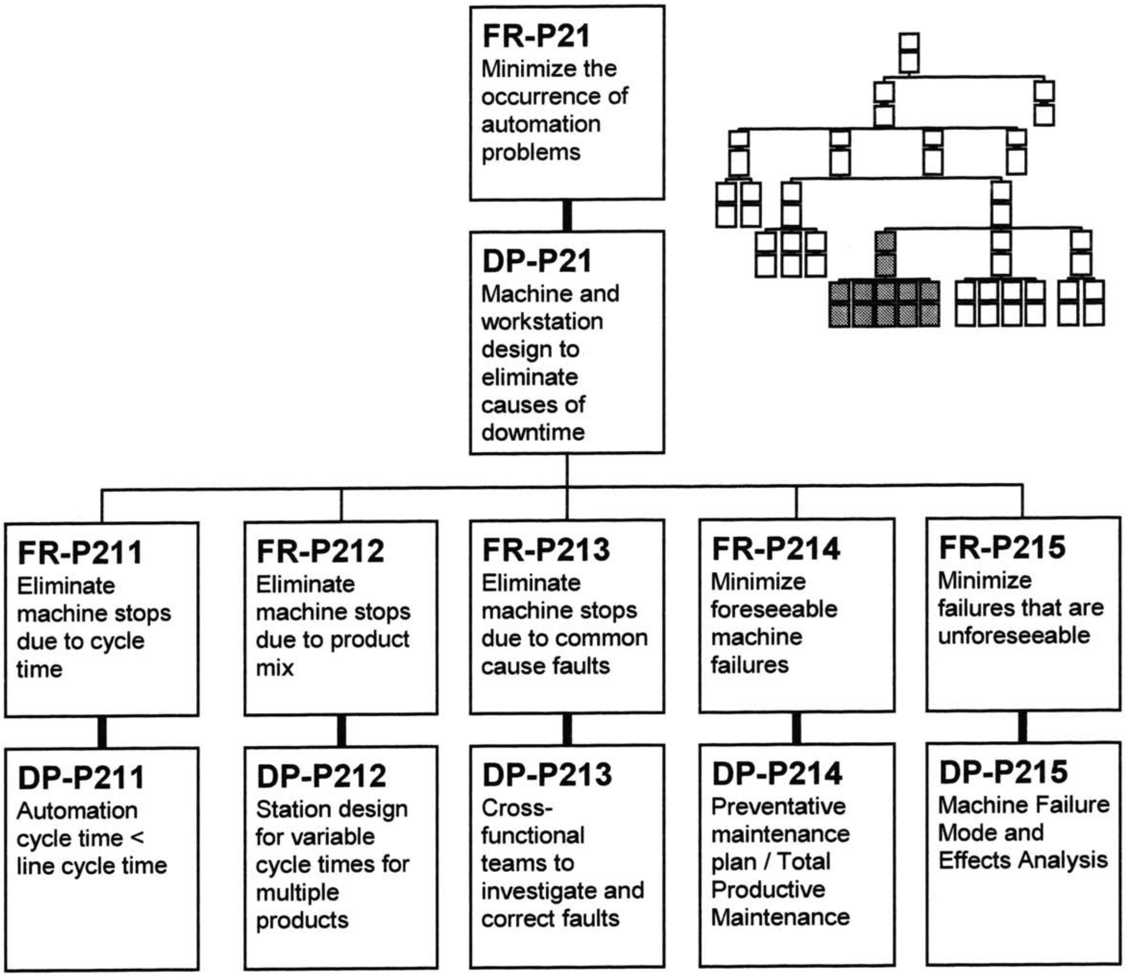


Figure 4.10 Automation Problems Decomposition

The second type of automation downtime is foreseeable machine failures. A machine failure occurs when a part of the machine, whether mechanical or electrical, breaks or in another way ceases to perform its design function. Many machine components such as motors, bearings, power supplies, etc., have probabilistic life spans that can be predicted based on the specific application. Failures of these components can be prevented, if they are replaced before their probability of failure gets too high. This probabilistic life span can be predicted analytically during the design of the automation, or observed empirically during its operation. Based on this information, a preventative maintenance plan can be established where specified critical components are replaced on a defined interval. This interval can be shortened or lengthened, based on the observation of failures (or the lack thereof). The cost of replacing components before their ultimate failure should be significantly less than the implicit cost of process disruptions. This preventative maintenance should be performed in addition to lubrication and adjustment that is typically performed on automation as directed by its manufacturer or by maintenance standards.

The last type of problems is machine failures that are unforeseeable. If failures cannot be predicted, they cannot be prevented. Therefore, the design parameter to minimize these problems is to make the failures foreseeable, through machine failure mode and effects analysis (MFMEA). Data for the MFMEA should be gathered based on engineering knowledge of the equipment and empirical observation of its performance. This information should be used to design more reliable machines and use preventative maintenance to prevent the failures that cannot be designed out.

Individual machine fault data can be used to monitor these FR's, with specific focus on the MTBF of individual faults, or the inverse of MTBF as discussed earlier. In addition, records should be kept regarding the occurrence of failures of components that have been specified in the preventative maintenance program. If failures begin to occur more frequently than predicted, the root cause of failures can be investigated and the replacement interval shortened if necessary.

4.5.5 Problem Response Time

Once problems occur, it becomes necessary to minimize the time that it takes to identify the existence of the problem and get the correct personnel working to fix it. The first step is to be sure that someone is responsible for monitoring each area of the manufacturing system and alerting personnel to problems. In some areas this may be the job of supervisors, machine operators, or line workers. The key points are that it should be someone who is usually always present in the area to see a problem, and that the person has been given clear responsibility for that area. In some parts of the Ford paint shop, the processes were completely automated and no one was around to identify problems. Video cameras were set up in these areas, and a skilled tradesperson was responsible for monitoring all of the areas and alerting others if problems occurred.

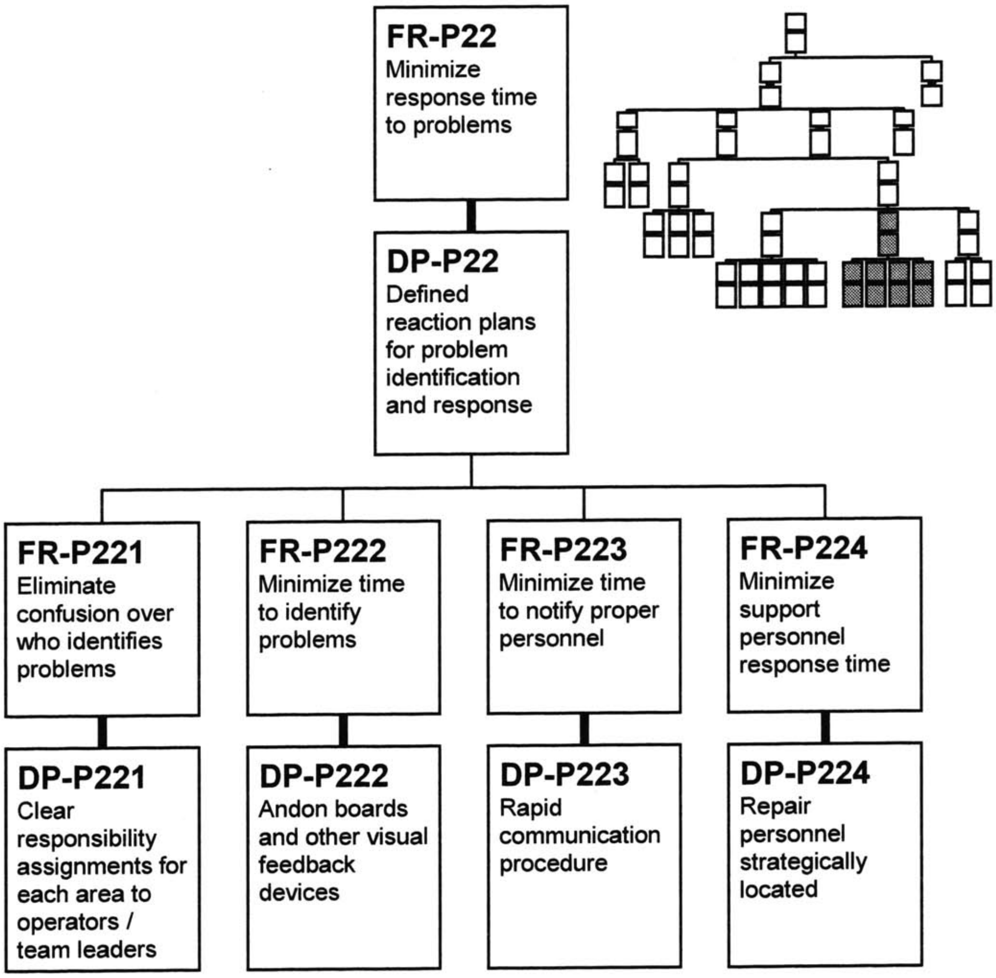


Figure 4.11 Response Time Decomposition

The second requirement is to make it easy for the defined person to recognize that a problem exists. This can be accomplished with andon boards, visual or audio feedback devices, electronic monitoring, or other methods.

At this point, the designated person must be aware of the proper person to contact to resolve the problem. In some cases, he or she may be responsible for solving the problem without help, but most times support personnel (engineering, skilled trades, etc.) must assist. There must be clear procedures telling whom to contact for various problems, and a means of rapid communication such as wireless radios.

Once support personnel have been notified, their time to respond must be minimized. This can be most effectively accomplished by having these resources strategically located throughout the system, to ensure that they are close to the most likely or most critical problem areas.

As stated earlier, there is no practical way to measure the time to respond in absolute terms. Observation and personal judgment must be used to manage this aspect of throughput.

4.5.6 Time To Repair

The last area to decompose in this design is the time to repair automation problems. This area is divided into two categories: minor problems and major problems. Minor problems can be most effectively solved by training machine operators or line workers to correct them. This allows these workers to have only a few problems they need to be able to correct, so they can be more familiar with the procedures to quickly correct them. The repair of major problems depends on well-trained repair personnel that are familiar with the automation.

Mean time to repair measurements for specific machine faults and failures should be used to gauge the performance of the system in this area.

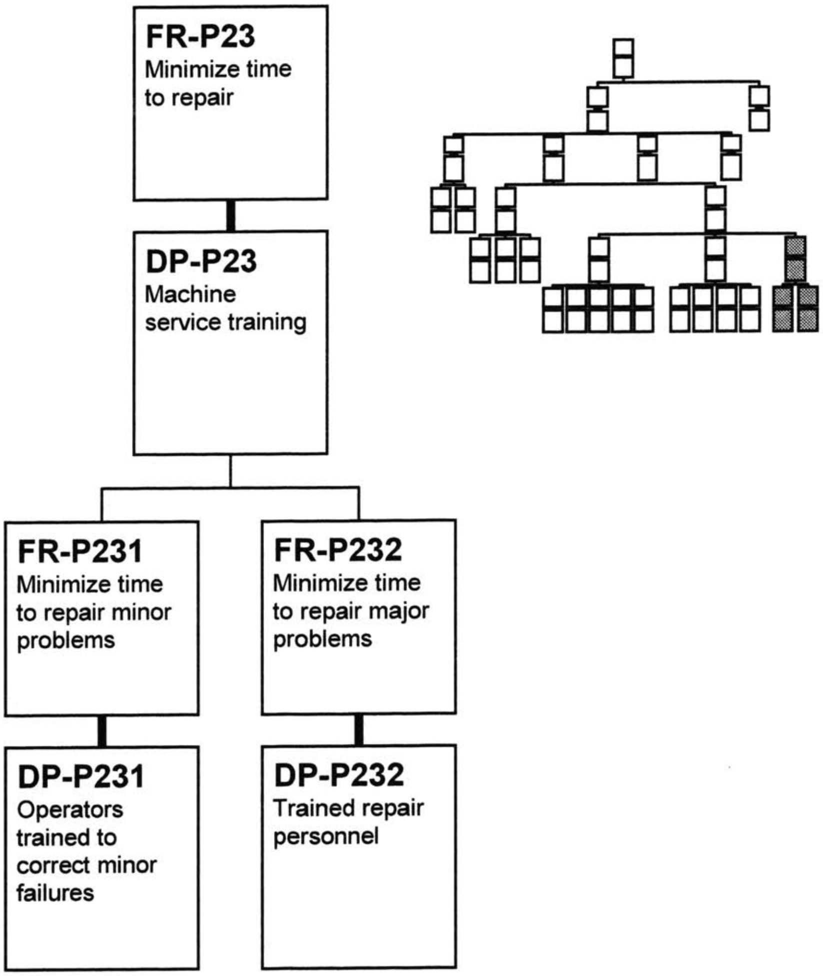


Figure 4.12 Time to Repair Decomposition

4.6 Design Summary

Since the system design decomposition shown here is partially coupled in some areas, the order in which the functional requirements are satisfied is relevant. In general, the design parameters should be implemented from left to right in the decomposition. For instance, in Level III, every attempt should be made to minimize lost throughput before process overspeed is used to correct for the throughput loss. This is doubly important in this case because overspeed could cause additional lost throughput. In Level II, improving quality, minimizing process disruptions, and eliminating the causes of slow cycle time should take place before placing buffers between processes as a way to increase throughput. Optimizing the system in this order will result in the best overall performance.

	Parameter	Measurement
Level III	Produce to takt time	Actual takt time / JPH
	Lost throughput	Overall Equipment Effectiveness
	Overcome lost throughput	Process overspeed
Level II	Quality losses	Quality %
	Process disruptions	Availability %
	Operator line stops	Minutes/shift operator line stops
	Automation line stops	Minutes/shift automation line stops
	Slow process cycle time	Performance Efficiency %
	Process interactions	Blocked/Starved %
Level I	Quality defects	Individual defect locations and types
	Operator line stop causes	Individual workstation stop freq. & duration
	Occurrence of automation problems	Mean Time Between Failure or 1/MTBF
	Automation problem causes	Specific machine fault frequencies
	Response time to problems	Judgment and observation
	Time to repair automation problems	Mean time to repair
	Time to repair specific automation problems	Specific machine fault durations

Figure 4.13 Design Parameters and Measurements

Figure 4.13 summarizes the parameters that were identified in the design decomposition, and the measurements that are associated with each of the parameters. A manufacturing system that is properly designed to control, monitor, and improve throughput must include the tracking of each of these measures and the feedback of these measures to the appropriate levels of the organization. Use of this approach to measure and identify specific causes of throughput loss in the Ford Paint department resulted in a much better understanding of the manufacturing system and the reasons for throughput loss, so that resources could be directed toward solving specific problems. This decomposition also serves as the basis for the proposed feedback system described in Chapter 5.

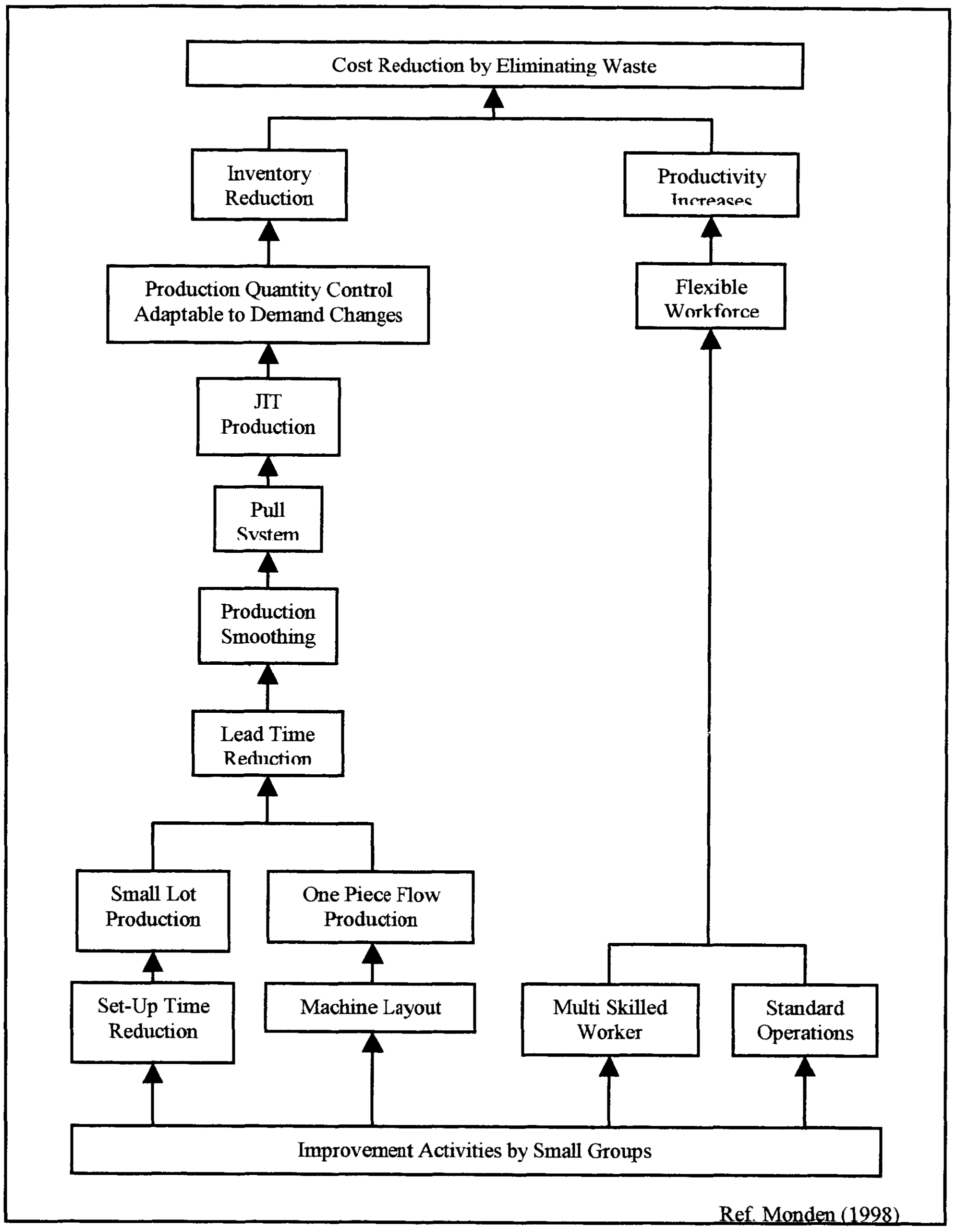
Chapter 5: Design of the Information Feedback Process

Chapters 3 and 4 described the methods and requirements to identify bottlenecks and control throughput and throughput losses in a manufacturing system. This chapter will describe the information feedback that is required for each level in the system to be able to perform these tasks, why it is essential to provide this feedback, and how the Ford Production System methods do and do not accomplish this feedback.

Much of the basis for this chapter comes from the literature, but the work performed as part of the internship at Ford, most specifically the interviews described in section 5.8 and Appendix B, served to focus this information toward those areas which are most appropriate for Ford and the Ford Production System. Unfortunately, there was insufficient time on the internship to implement much of this feedback structure, so little empirical evidence exists with which to judge its effectiveness. Where appropriate, the current processes used by Ford and FPS are discussed in section 5.7, to describe how they fit into the desired feedback system.

5.1 Why is feedback important?

Feedback is generally acknowledged as an essential ingredient for effective management. We know from psychological research that people need knowledge of results in order to accomplish performance goals and improve their performance over time. Psychologists have also long recognized the value of feedback to enhance job challenge, increase motivation, and facilitate learning when the information is meaningful and given in a helpful way (London, 1997). While it is necessary for management in a manufacturing organization to obtain feedback information regarding the performance of the system (at Level III, as described in Chapter 4), it is as important or more important for workers that operate and control the system from minute to minute to have effective feedback regarding their performance.



Ref. Monden (1998)

Figure 5.1 Toyota Production System Element Hierarchy

Numerous researchers and practitioners of lean manufacturing and the Toyota Production System have identified improvement efforts by shop floor work teams as a core and foundational element of achieving lean production. Monden (1998) identifies a hierarchy among the elements of the Toyota Production System, as shown in Figure 5.1. The first and most basic of these is improvement activities by small work groups. The entire system is built on the philosophy and successful implementation of continuous improvement through small work teams (Welnick, 2001). Hayes, Wheelwright, & Clark (1988) declare that the vision of the future manufacturing organization depends more upon the line workers' ability to solve problems and make decisions. Cassidy (1999), in a throughput improvement project similar to this one, similarly noted that the major weakness of the throughput effort lay in the realm of labor relations. There was a lack off mechanisms to engage the workforce, and therefore much untapped potential.

Manufacturing companies desiring to improve their operations have taken note of this, and many have implemented a team structure for line workers. The United Auto Workers explicitly endorsed team concept in the national union contracts signed with Ford and GM in the fall of 1987, and the team concept is growing in other industries as well (Parker & Slaughter, p.4). The team structure was influenced both by the success of Japanese auto companies, Toyota's NUMMI in particular, and by the Quality of Work Life programs conducted in the late 1970's and early 1980's (Parker & Slaughter, p.8). Many of these teams were referred to as Quality Circles.

As useful as the team structure is in fostering improvement, companies have had a difficult time achieving the level of performance and initiative from the teams as is typically reputed to happen at Toyota. In general, benefits can only come when the team is empowered. Empowerment means giving the workers the power and responsibility to improve the process (Camhi, 1991). Ancona, et.al. (1999) noted that primitive Quality Cirlces will never provide more than incremental gains in productivity. Large gains can only come from self-managed or high-performance teams whose members are truly empowered to organize their work and make decisions.

However, Besser (1996) in an interview with a former Toyota employee who was working at another manufacturing company, recorded the following comment regarding teamwork at his new company:

> If you turn over the reins to them (the line workers), and say, "Okay make suggestions. What would you do?" either, number one, they don't come up with anything; number two, they come up with the stupidest, dumb things you've ever heard; or number three, they just want to goof off all day.

Tai (1991) and Camhi (1991) also observed instances where teams existed in a manufacturing plant, but were clearly poorly utilized or ineffective at creating improvement. Clearly, simply creating a team structure and instructing or empowering them to make improvements is not enough.

Worse than that, empowering or even simply creating a team structure without the teams aligned toward organizational objectives can be potentially dangerous. Besser (1996) noted that Toyota runs a risk in nurturing work teams because the solidarity developed between team members could be used against management and management efforts toward goal achievement, if the work team norms and goals become incongruent with Toyota philosophy. Parker & Slaughter (1998) also observed that the new structure can make unions potentially more dangerous if workers take collective actions to disrupt the system. Senge (1990) states that to empower people in an unaligned organization can be counter productive. If people do not share a common vision and do not share common "mental models" about the business reality within which they operate, empowering people will only increase organizational stress and the burden of management to maintain coherence and direction. Of course, if this happens, the company has deeper-rooted organizational problems. The team structure allows those problems to surface, where they were previously kept hidden, which could have positive or negative consequences.

While it is certainly true that improvement activities by work teams are fundamental to the manufacturing system, those improvement activities do not spontaneously appear. Employees must have the proper tools and environment to succeed (Welnick, 2001, p.46). It is not simply a matter of whether or not the teams are truly empowered, either. There is some debate regarding the extent to which teams in lean production plants are truly empowered. Kenney and Florida (1993) stand alone in depicting teams under lean production as "self-managing" (Rinehart, et.al., 1997, p.86). In some plants, teams make decisions regarding work allocation, job rotations, and production scheduling, but supervisors and engineers must still have some control over the system if it involves cross-coordination between several teams or quality-critical operations. Flinchbaugh (1998) at Chrysler referred to teams as "semi-autonomous."

The environment that is necessary to create self-managing or empowered teams is one in which all people working in the manufacturing system have sufficient feedback so that they can determine the requirements of the system, see the performance of the system relative to those requirements, and uncover their individual impact on that performance. In a traditional hierarchical manufacturing organization, management possesses the knowledge of system performance and problem areas, but production workers possess detailed knowledge of the process and operations and how improvements could be made. Feedback to production workers might be limited to management's communication of poor performance to individuals who they feel need to alter their actions. Large-scale, continuous, sustainable improvement requires that someone possess both the knowledge of the operations and the knowledge of system performance, and the most effective means to accomplish this is typically to transfer the knowledge of system performance to the work teams.

Tai (1991) observed that workers at several different facilities he studied expressed the similar feeling that although they were part of a team, they did not truly improve the team's quality and delivery until they understood how their work impacted others. Liker (1998), in a case study of the Sunshine Corp., an automotive sunroof producer, also noted that an essential characteristic of its continuous improvement process was management's willingness to share information, whether financial or operational, and their focus on making sure that workers understood the information. Camhi (1991) interviewed a manager at a Digital Equipment Corporation plant, that stated, "We keep relearning that teams lose focus and flounder when they stop using their data. Employee involvement must be centered on data use." It is unlikely that a work team can become truly self-managing and create large-scale improvement if they do not have the ability to determine where problems exist or determine if and why changes they make result (or do not result) in an overall improvement in the system performance.

Proper use of performance feedback can help to build self-efficacy in team members and foster a learning environment. When team members can see both the positive and negative results of their actions, performance will be higher and improve more rapidly. If the outcome is positive, the team builds the confidence that they possess the skills necessary to achieve success. This confidence increases the likelihood of future success (Nash, 1985, p.102-104). If the outcome is negative and the team can see the cause-effect relationship between their actions and the outcome, then adjustments can be made. In this case, simple success/failure information is not sufficient. Rather, accurate, timely, specific feedback regarding an understanding of the cause-and-effect relationships involved in performing the task is necessary (Lindsley, 1995, p.653).

In addition, good feedback can increase job satisfaction and motivation. Lawler (1973) writes that social contact is an innate need that exists in most human beings, and that jobs that do not provide opportunities for social contact have higher turnover and absenteeism rates. This often results from mechanical and architectural designs that do not consider employees' needs for social relationships. Performance feedback on the overall system and the individual operation, combined with the team structure, can help to mitigate this problem. The opportunity to take on responsibility and make meaningful changes to one's job (and see the results) can allow people to experience achievement, competence, and self-realization, satisfying higher-order psychological needs and increasing their motivation (Lawler, 1973, p.107). However, Lewin (1944) and Argyris (1964) argue that individuals experience higher-order-need satisfaction only when they LEARN that they have accomplished something they believe is personally worthwhile or meaningful. Therefore, even if a person's job entails meaningful responsibility and results in a worthwhile outcome, that person cannot experience higher-order-need satisfaction unless he obtains some feedback about how he is doing.

In general, feedback has the following positive effects (London, 1997, p.14-15):

- Positive feedback is reinforcing in and of itself. Even if it does not lead to some material outcome, such as more money, people appreciate knowing when they have done well. Such feedback heightens their sense of achievement and internal motivation.
- Feedback increases employees' abilities to detect errors on their own. They know what performance elements are important and what levels of performance are expected. As such, feedback sets standards of performance, and employees learn to evaluate themselves against these standards.
- Feedback enhances individual learning. Employees realize what they need to know and what they need to do to improve. Seeking self-knowledge is a prerequisite for, and motivator of, growth and improvement.
- Feedback increases the amount of power and control employees feel. This applies to both the source of feedback and the recipient. Providers of feedback understand how information can improve others' performances. Recipients of feedback recognize how information helps them take control of their own performance. Regular feedback helps them feel they can cope with performance problems by being able to make incremental changes in their behavior and see the effects.
- Feedback increases employees' feelings of involvement in the task. They recognize how they contribute to the task, and they feel a sense of task ownership and importance.

5.2 The goals of a feedback process

The feedback process in a manufacturing system should serve to communicate relevant information regarding process performance to those in the system that can make use of it to affect their behavior. This includes people at all levels of the organization, and means that people at different levels need to receive different types of information, and different levels of detail, depending on their specific job. Ideally, the feedback should allow every person in the system to answer the following questions:

1. Do you know if you (individually) are doing your job correctly, if the outcome meets the requirements?
2. Do you know if the overall system is meeting its requirements? If it is not, do you know where the problem is?

Question #1 relates to one of the key things that Spear & Bowen (1999) say Toyota workers use to facilitate problem solving and learning. If one cannot determine whether one's outcome meets requirements, it is difficult to identify or solve problems and learn from them. Question #2 attempts to create an environment where everyone thinks about his or her relationship to the system as a whole. One of the benefits attributed to cellular layouts in lean manufacturing is that each person in the cell is close enough to the other processes that the entire system is visible. Each person can see the performance of the whole system, and see his or her affect on that performance. This is difficult to accomplish in an automotive assembly plant, even though the entire plant is arranged in a flow-based layout. The system is so large and complex that workers in one area cannot see other parts of the system. In this case, feedback devices must be used to achieve this system-level viewpoint.

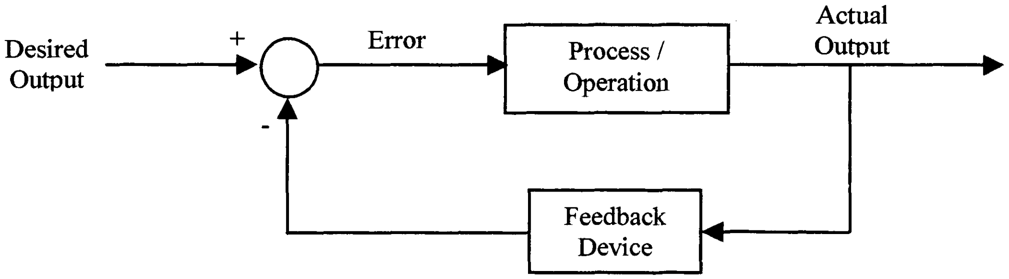


Figure 5.2 Control System

The feedback process essentially acts as a control system. The fundamental principle of control theory is to determine the "error" between a desired result and the actual result and take corrective action to eliminate the error. Actual output is measured and then compared against the desired result. The "error" is communicated to the controller, which determines and executes the necessary corrective action (Stec, 1998, p.42-43). The speed of the feedback is a key parameter. At lower, more detailed levels of measurement, the feedback should become more rapid, approaching real-time. The corrective action must be made quickly, not only to prevent the situation from becoming worse, but also to facilitate learning. If the system is a dynamic one (as most are), the information must be obtained and acted upon rapidly enough such that the status of the system has not radically changed (Sullivan, 1997, p.23). The most effective analysis and improvement will occur if the action that caused the undesirable output is still fresh in the mind of the person who performed that action.

Some other criteria for the feedback process are as follows:

1. It should be data-driven, objective, unbiased, impersonal but specific. The key here is to ensure that those receiving the feedback can trust it, and make use of it for corrective action and learning. Preferably, the feedback should not have to pass through the hands of a supervisor or anyone else that a worker may not fully trust. The feedback must take place consistently whether the output is positive or negative, so that the recipient can take actions and observe how those actions affect the result.

2. It should be timely, local, and presented clearly. People need feedback fast enough so that they can connect their behavior to changes in the outcome, detailed enough so that each person can observe how their individual behavior changes the outcome, and simple enough so they can understand it (Arnow, 1993, p.51-52).

3. It should allow everyone to become a "problem-solver." People who do not have knowledge of the problems will not work to develop solutions.

4. It should align the organization toward achievement of the same goals. The requirements of the system and of each operation should be clear.

5. It should properly align authority with responsibility. People should be held accountable for their own actions, not those of others (Arnow, 1993, p.51-52). Constructive feedback allows people to attribute good or poor performance to internal or external causes (London, 1997, p.22).

It is virtually impossible to prescribe exactly what kind of feedback should be present in a manufacturing system. Especially for the detailed measurements, it is necessary to examine each job in the organization and determine: 1. What is the required outcome of this operation? 2. What information does this person need to determine whether the required outcome was achieved? For a paint sprayer, this may be the number of defects observed on a specific area of the vehicle or the length of time the line was stopped at that station. For an engineer, this may be the total downtime of a certain piece of automation or the number of preventable failures that occurred on that machine. The answers to these questions will determine the required feedback.

5.3 Types and methods of feedback

The three hierarchical levels of metrics (as related to throughput) were described in Chapter 4. In general, metrics for quality, lead-time, or cost, or any factor of interest could be categorized into these three levels, but this thesis will deal solely with throughput metrics. Metrics can also be fed back into the system using any of three different methods: periodic charting and reporting, on-demand electronic data, and real-time feedback displays. The difference between these methods and the intent of each one will be discussed here. Figure 5.3 shows that each level of feedback can use each of the three methods.

		Feedback Method		
		Periodic Charting and Reporting	On-Demand Electronic Data	Real-Time Feedback Displays
Feedback Type	Level III Metrics	Yes	Yes	Yes
	Level II Metrics	Yes	Yes	Manual and automation downtime only
	Level I Metrics	Key problem areas only	Yes	When practical and useful

Figure 5.3 Feedback Types and Methods

Periodic charting and reporting means that someone takes the time to record a measurement onto a chart every day, week, or other defined interval. The chart or report is posted in an area where the intended recipients of the feedback will be able to observe it, or it is distributed to those individuals. This could use a measurement board at the team's work area, a workstation, team meeting area, or conference room, or could be distributed to managers, engineers, or repairmen periodically.

On-demand electronic data typically is collected automatically by a machine controller, or is entered into an electronic system by an operator, inspector, etc. Feedback of this type is active as opposed to passive, meaning that the information is only transmitted if the recipient consciously seeks it. Typically a database system might be constructed to continuously track certain metrics, which could then be accessed using pre-programmed reports if a problem was suspected in a certain area. This type of data can be both very broad in scope and very specific and detailed, since it does not require someone's time to report it and it need not be simplified down to one simple chart or graph.

Real-time feedback is also typically done electronically, but the feedback is passive instead of active. In this case, andons, scheduling boards, kanbans, and other visual displays are used to communicate information that everyone needs or should be aware of at all times. Visual control is a core feature of the Toyota Production System, and is used to ensure that anyone can tell the status of the system at a moment's glance (Cassidy, 1999, p.27). Real-time feedback can be used to overcome a plant layout that does not facilitate people's connection to the outputs of the system or their individual jobs. Ideally, everyone in the system should be able to tell immediately whether the outcome of their work met the requirements, whether the outcome of the system is meeting the requirements, and if those two are connected.

The speed of the feedback loop gets faster as one moves from periodic charting and reporting to real-time feedback. Faster response is necessary when trying to identify problems that are transient, or depend on a set of input conditions that may change rapidly. In these cases, learning the relationships between the inputs and outputs requires feedback response that is fast enough for people to connect the two in time. When feedback is delayed, actors may continue to employ inappropriate strategies or effort (Lindsley, et.al., 1995, p.653).

5.4 Real-time feedback displays

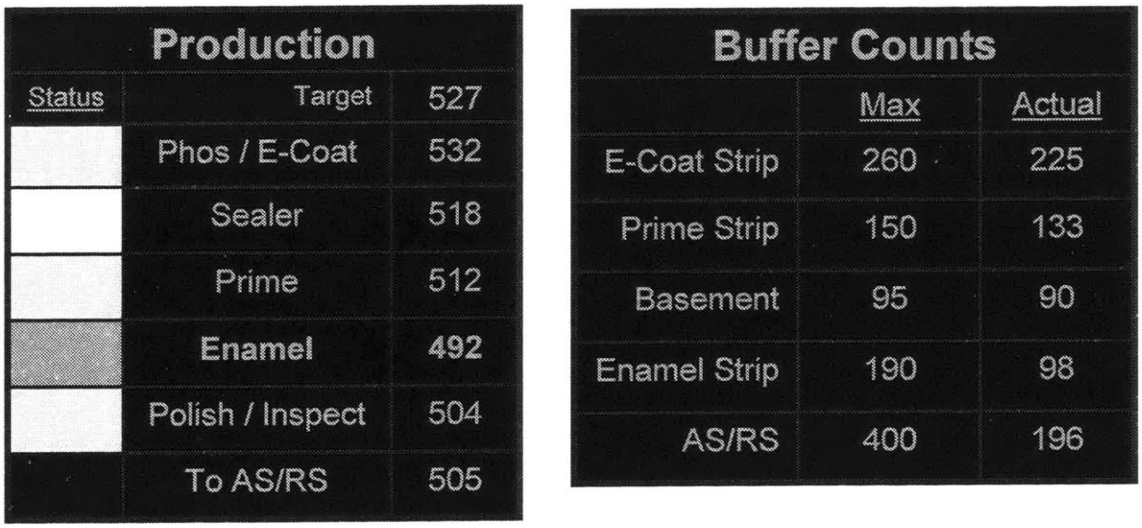
As with all three feedback methods, real-time feedback displays can be used to communicate system performance at Levels III, II, & I. These sections use the Ford Paint department as an example to show what type of feedback is appropriate for each method. Many of these do not yet exist in the Ford Paint department, so this is meant to be a proposal for what could be done in this setting.

Real-time feedback should be used to feed back information that needs to be communicated quickly. This includes outcomes that change frequently, that are transient and whose transience makes them difficult to observe in other than real-time, or that require an adjustment as fast as possible to prevent the system outputs from becoming any worse. Real-time feedback should be kept simple and clear, and be available to the recipients in a more or less passive manner

5.4.1 Level III - Production System Design Level

At the highest level, the important measure for throughput is simply throughput. Everyone in the system, and in each process in the system, should be able to tell whether the system is meeting its throughput target and whether that specific process is meeting its throughput target. Another key point that should be known to everyone in the system in real-time is the current throughput bottleneck. For this reason, it is necessary to communicate the throughput results of each process area, not just the one local process.

Figure 5.4 shows two types of andons that could be used to communicate this information. The production andon shows the target throughput at takt time and the actual throughput through each process area. It is easy to see that the Enamel process in this system is the current throughput bottleneck, even though it is uncertain why this is the case. More efficient identification of transient throughput bottlenecks would allow faster response to eliminate them and increase throughput to the required levels (Cassidy, 1999, p.47). In addition, if the primary throughput bottleneck is in the same process day after day, it will be obvious to everyone where improvements need to be made. The buffer count andon supplements the production information, by showing where the work-in-process is building up or draining down. This can help show whether the slowdown in Enamel is causing lost throughput at the upstream or downstream processes.



Production

Status	Target	527
░	Phos / E-Coat	532
□	Sealer	518
░	Prime	512
▓	**Enamel**	**492**
░	Polish / Inspect	504
	To AS/RS	505

Buffer Counts

	Max	Actual
E-Coat Strip	260	225
Prime Strip	150	133
Basement	95	90
Enamel Strip	190	98
AS/RS	400	196

Figure 5.4 Throughput Andons

Andons can be used to show the overall system output, but can also be used to show the current status of each process. Green, yellow, or red lights, either solid or blinking, can be used to signify six different running conditions of the process.

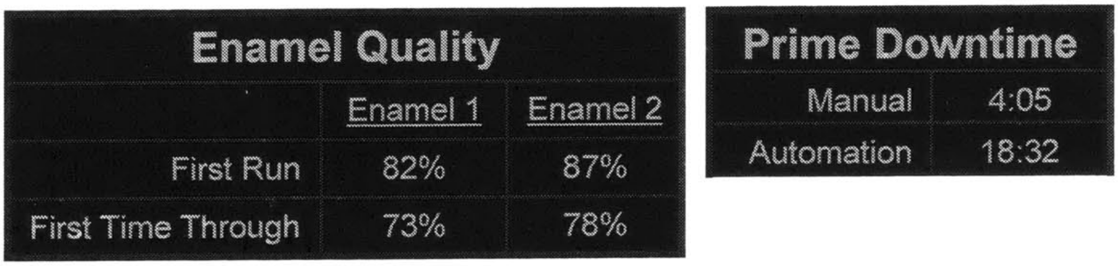
The Toyota Production System stresses the need for visual control such that anyone can tell the status of the system at a moment's glance (Cassidy, 1999, p.27). Placement of the andons is important such that everyone can see them, especially in areas that are very isolated from the rest of the system. On some Toyota lines, monitors connected to cameras pointed at the andon board are used to project the andon board into areas where the board itself is not visible (Eggert, 1998, p.37). Andons are not the only means to accomplish real-time feedback of high-level metrics. Toyota uses a musical tune on each process that plays when process throughput has fallen behind the takt time. What is important is not the specific method used to communicate, but rather that this fact be obvious to everyone.

One might ask why it is necessary for line workers to know the location of the throughput bottleneck if it is not their process. Wouldn't it be enough to show actual throughput in one area, and an additional signal to identify whether that process is the bottleneck? The answer is peer pressure. While it may seem manipulative, the goal is to make the system self-managing and visible, so that deviations from the target are automatically corrected. When everyone in the plant knows the location of the throughput bottleneck, it is a powerful incentive for line workers, supervisors, engineers, and others working in that area to correct the situation. Parker & Slaughter note that peer pressure can be a powerful force in the workplace. Most people have strong needs to be accepted and respected by the people we regard as our peers (Parker & Slaughter, 1998, p.22). Besser also observed that at Toyota, other team members are the primary appraisers of one's work. In a way, they, not management, are the evaluator of most importance (Besser, 1996, p.52-53). So long as a cultural norm exists that people feel performance is important, this visibility can be very effective.

5.4.2 Level II - Analysis Level

Level II feedback gets into more detail regarding why a process is not producing to takt time. Chapter 4 detailed several reasons why this might occur, but it is only necessary to communicate those metrics in real-time that are the direct result of people's actions, or can be directly corrected by people. These also need not be communicated to the entire system, but only to the areas that can have a direct impact on them.

In the paint shop, two items that should be communicated in this manner are paint booth quality and process downtime. The Enamel process is where the most variability occurs in the process, since units exiting the process must have a perfect paint finish. Trucks with small defects can be repaired offline, but many require an entire rerun coat of paint (and therefore take the place of a new unit that could be painted). Quality is a major contributor to throughput loss in the Enamel process. In most other processes, downtime is the only contributor to throughput loss that is directly under the control of those in the process. This can be broken into downtime caused by manual operations or by automation. Figure 5.5 shows displays that could be placed in each process. First-run quality shows only those units that do not require a rerun through the Enamel process, while first-time-through quality shows units that do not require any rework at all.



Enamel Quality		
	Enamel 1	Enamel 2
First Run	82%	87%
First Time Through	73%	78%

Prime Downtime	
Manual	4:05
Automation	18:32

Figure 5.5 Quality and Downtime Displays

At KTP, process downtime was displayed in real-time, but only that caused by manual operators. Quality information and automation downtime were only available through the computer monitoring system.

5.4.3 Level I - Manufacturing Process Level

There is a vast amount of information in Level I, so it is necessary to be more selective with the feedback that is performed with real-time displays. Once again, real-time displays are appropriate when quick feedback is necessary to quickly correct a problem or identify cause-and-effect relationship in operations with high variability. The Enamel process is one such area in the paint shop. One speck of dirt, the presence of an impurity in the air, or a bad paint mix can ruin an entire paint coat. In addition, inspection of the paint coat does not take place until 45-50 minutes after the unit is painted (since the unit travels through a bake oven), making it often difficult to connect actions to their results.

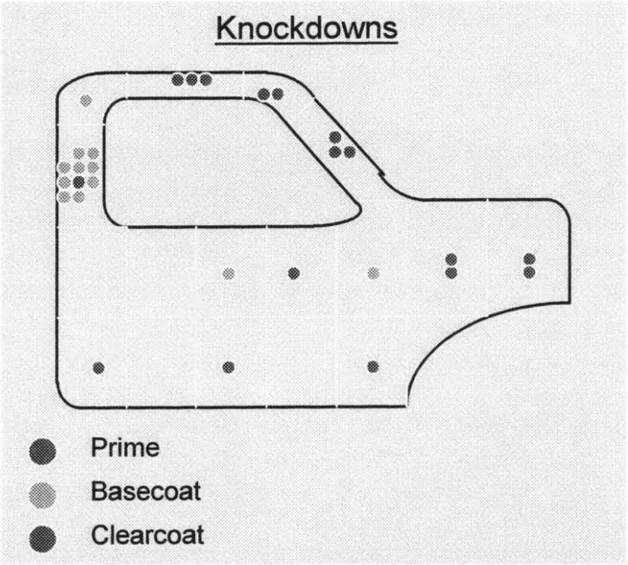


Figure 5.6 Detailed Paint Quality Feedback

A display such as shown in Figure 5.6 can help to pinpoint paint problems to a specific operation in the process, by pinpointing on which part of the vehicle the defect was located. This display shows only one part of the vehicle, but each surface on the truck must be shown. Defects can be attributed to either the basecoat or clearcoat operations (both part of Enamel), or even the Prime process if they were not properly repaired earlier. While there are many other factors that could cause paint problems, this display could help to identify some of them[12].

Andons could also be used in Level I, which is where they are found most frequently in automotive plants. An andon board for a specific process could pinpoint the status of each operation, show the locations of faults, identify areas that require tool changes or cleaning, or show the stations where workers have stopped the line. Andons such as this can help repairmen, team leaders, and others to quickly identify and resolve problems.

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[12] A six-sigma analysis of paint defects would want to include paint color, mixing batch, work crew, # of coats, and many other factors besides those shown in this display.

5.5 On-demand electronic data

A computer database can record and store vast amounts of information related to process performance. Real-time displays are limited in the amount of information they can convey, since the display must be kept simple and easy to understand, and displays are more expensive to buy and set up in a manufacturing plant. On a computer interface, reports can be generated that are very rich in content, since they convey only the information that is requested by the user. Information available in this format is active, meaning someone must be actively looking for it in order for it to be useful. Feedback performed using this method must be of a form that is only required for specific problem identification, and only needed by someone who has access to a computer terminal. Generally but not always this includes management, engineers, repairmen, and machine operators.

5.5.1 Level III - Production System Design Level

Everything shown for Level III on the real-time displays (throughput, buffer counts) can also be shown in real-time on a computer system. This is useful in order to limit the number of real-time displays that are needed in the plant. In addition, throughput, throughput rate, and OEE data can be calculated and recorded for previous shifts, so the history and average over time can be observed.

5.5.2 Level II - Analysis Level

Similar to Level III, overall quality data that is on a real-time display can also be made available on a computer system. In addition, an electronic system that tracks the movement of units through the manufacturing system and records the actions of each process controller is capable, if set up properly, of recording and making available all of the other elements of the Level II decomposition, such as manual and automation downtime, machine cycle time performance, and blocks / starves.

Figure 5.7 shows an automated measure of the gross cycle time of a few processes. This measurement is taken by measuring and averaging the amount of time between each unit entering the process, discounting for times when the machine is down, blocked, or starved. The measurement may fluctuate with the actual product mix from day to day, but should stay relatively constant over time. These results can be compared to the cycle time that is expected based on the design of the process, and also be observed for changes over time. In this graph we can see that the E-Coat Scuff process had a significant increase in cycle time around 6/12/01. This data can be used to identify problems with material handling conveyors or unintended changes to the process parameters.

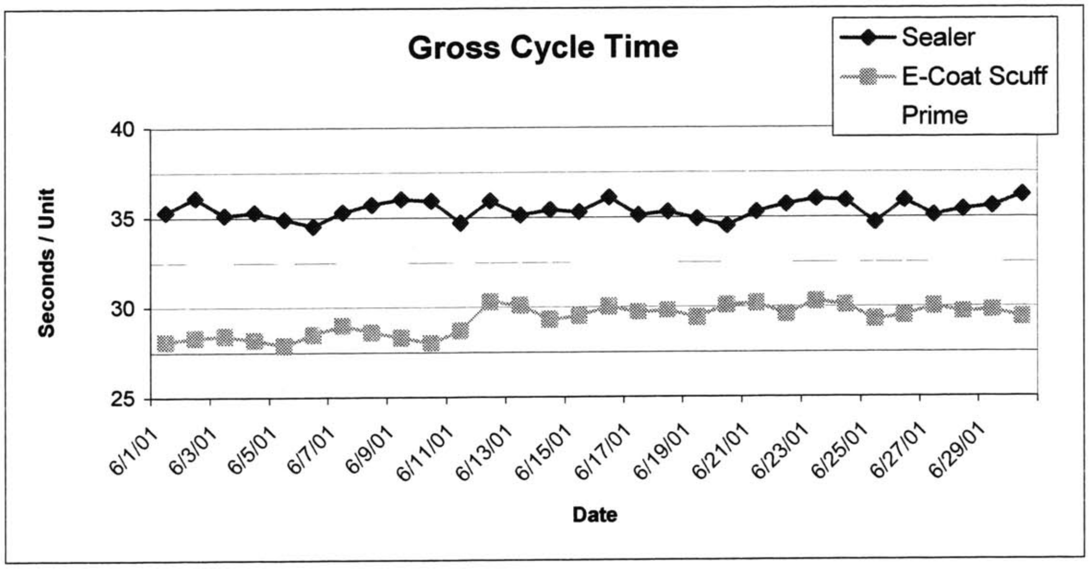

Figure 5.7 Automated Gross Cycle Time Measurements

Figures 5.8 and 5.9 show process downtime reported in two different ways. Figure 5.8 shows the automation downtime for the Prime process for each shift over a two-week period. Also, the shifts are identified by which of the three crews were working, and the one-week average of the downtime is tracked over time. Here we can see that the downtime is increasing over time. Another report could be devised that summarizes the performance of each crew, to determine if knowledge or skills exist on one crew that results in better performance.

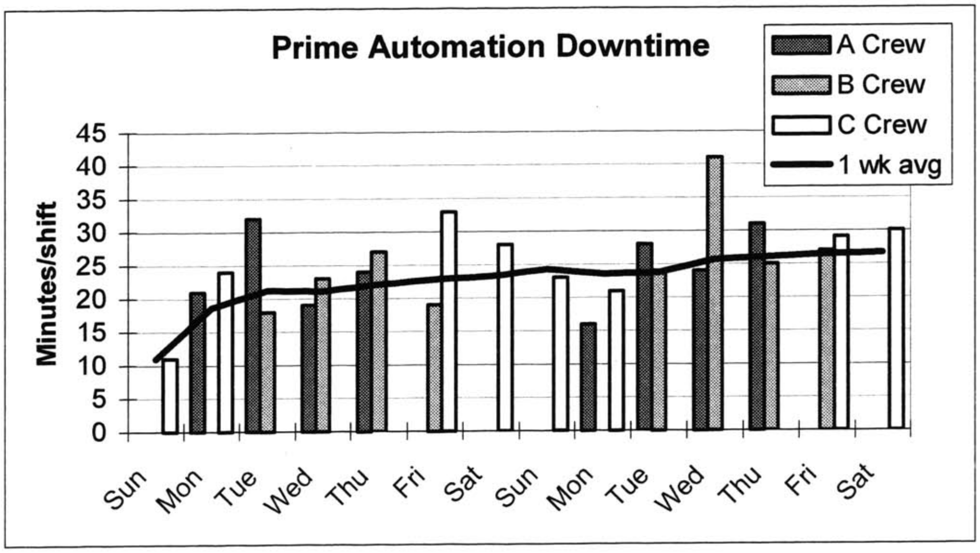

Figure 5.8 Automation Downtime Two-Week Summary

In Figure 5.9, the automation downtime data is displayed for only one day, but broken up into the four operations that make up the automated portion of the Prime process. While this feedback does not show the trend over time, it can allow personnel to respond to problems quickly by identifying which area of the process is causing the most downtime. This information is most useful to engineers and repairmen.

Blocked and starved information can be made available on a computer in real-time as well, which would facilitate the tracking of problems to their source.

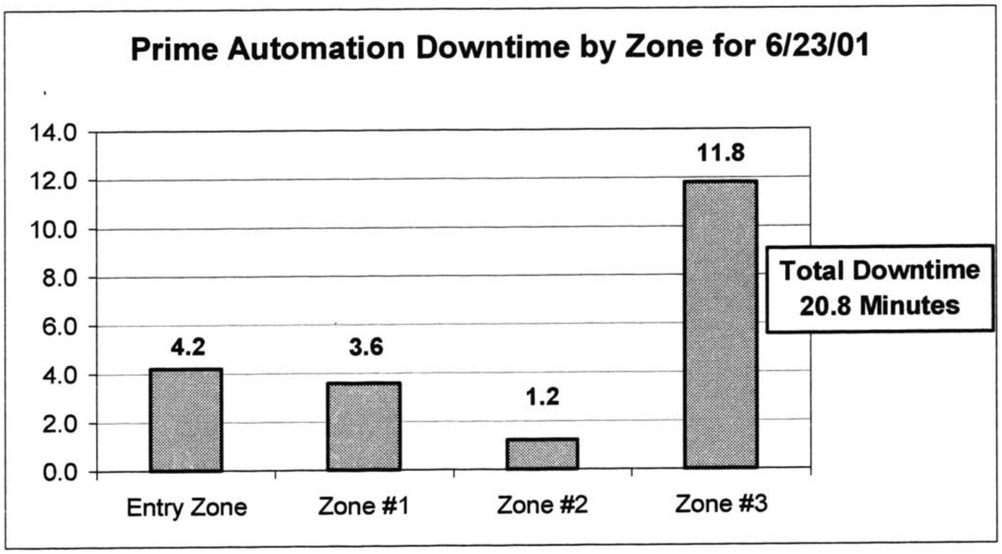

Figure 5.9 Automation Downtime by Zone

The graph used in Figure 5.8 was created manually at KTP and used quite extensively during the internship. By seeing the trend over time, as well as the daily performance relative to the average, engineers and operators could easily relate the occurrences of a specific day to their affect on the overall performance of the process.

5.5.3 Level I - Manufacturing Process Level

At Level I, a computer database system can record and analyze every single fault or condition that occurs on a machine. This data can be extremely useful for problem solving, but can also be cumbersome to work with. A good computerized feedback system will allow this data to be pared down into that which is useful. Figure 5.10 shows a detailed fault listing for the Prime process on a single shift. Machine controllers typically generate many more faults, alarms, warnings, and conditions regarding their current running state. In the case of a robot controller, a series of twenty faults may all be due to one problem, and the operator's attempts to fix that one problem. Figure 5.10 has boiled down the listings to only those faults that cause the line to stop, and eliminates any faults that occur while the first one is still active.

Figure 5.11 summarizes the faults into the frequency and total duration of each specific problem. This summary can be used to see exactly where the most problems are occurring in the Prime process. Much of this data was available in the data tracking system used in the Ford KTP Paint department, but it was not readily available to skilled tradespersons, operators, or work teams that might make productive use of it.

Even these fault listings, because a machine controller generates them, are not always terribly useful. The fault tells only what went wrong, but does not provide any interpretation as to why it went wrong. A separate system that allows for human interpretation of the larger problems, by an operator or engineer, would be a useful supplement to a system like this.

Significant quality information can also be gathered electronically in Level I. When a defect occurs, manual inspectors can enter information regarding the defect in addition to that shown in the real-time display shown in Figure 5.6, such as the type of defect, time recorded, and the remedy required. This data can be made available on a computer by using Figure 5.6 to query the information on a specific defect.

Prime Line Stop Faults for 6/23/01		
Time	**Description**	**Duration (sec.)**
6:03:52	Man. Sta. #1 Line Stop	16
6:15:56	Zone #1 Style ID Fault	62
6:26:52	Zone #3 Photo Eye Fault	37
7:02:53	Man. Sta. #3 Line Stop	20
7:52:09	Zone #3 Robot High Current Alarm	132
7:56:34	Man. Sta. #4 Line Stop	67
10:05:54	Zone #2 Fluid Pressure Low	73
10:35:14	Entry Zone No Data Fault	129
10:45:57	Zone #3 Photo Eye Fault	69
11:01:30	Zone #1 Style ID Fault	82
11:07:08	Man. Sta. #1 Line Stop	18
11:07:22	Entry Zone No Data Fault	123
11:51:39	Man. Sta. #3 Line Stop	16
12:53:56	Man. Sta. #4 Line Stop	36
15:03:05	Zone #3 Robot High Current Alarm	93
15:32:19	Zone #1 Robot Fault	72
15:43:01	Man. Sta. #4 Line Stop	27
16:00:38	Zone #3 Robot High Current Alarm	125
16:16:15	Zone #3 Robot High Current Alarm	134
16:27:55	Zone #3 Robot High Current Alarm	118

Figure 5.10 Detailed Fault Listing

Prime Line Stop Summary for 6/23/01		
Description	**Frequency**	**Duration (sec.)**
Zone #3 Robot High Current Alarm	5	602
Entry Zone No Data Fault	2	252
Zone #1 Style ID Fault	2	143
Man. Sta. #4 Line Stop	3	130
Zone #3 Photo Eye Fault	2	106
Zone #2 Fluid Pressure Low	1	73
Man. Sta. #3 Line Stop	2	36
Man. Sta. #1 Line Stop	2	34
Zone #1 Robot Fault	1	72
Total-	**20**	**1449**
	Total Minutes-	**24.1**

Figure 5.11 Fault Summary

5.6 Periodic charting and reporting

Charts and reports are useful for data that does not need to be acted upon in real-time, such as tracking long-term improvement trends or observing the results of process design changes, new preventative maintenance schedules, or line rebalancing. They are also mostly used for reflective measurement of results, and not the direct observation of current performance.

Charts and reports in a plant are sometimes part of a Statistical Quality Control, Six Sigma, or lean manufacturing program implemented by the corporation. However, the existence of charts and reports should not be confused with the use of charts and reports. Camhi (1991, p.55) visited numerous plants where charts were posted, but further examination revealed that no one in the group ever looked at the charts and no decisions had ever been made because of them. He observed some groups in various plants with very fancy computer-generated charts that did not use them for anything, apparently, but decoration. Above all, charts and reports that are generated must be useful to people in the system, communicating information that is relevant in a clear and simple manner.

5.6.1 Level III - Manufacturing System Design Level

Reports can be created at this level that show the overall throughput rate or takt time of the manufacturing system and the amount of overtime work that is required to make up for inadequate throughput. This information is valuable for everyone in the manufacturing plant to have, from plant management to line workers. While these metrics are too high for workers on the floor to be able to connect their actions to them, it is still necessary to be aware if there is a problem.

5.6.2 Level II - Analysis Level

One of the most useful graphs that captures almost all of the throughput information in Level II is the OEE stack chart shown in Figure 5.12. This shows the OEE percentage over time for one particular process, but also shows the relative contribution of the OEE components to the total lost throughput. In this particular graph, one can see that the availability and quality of this process has improved considerably over time, but the overall OEE has not improved. Starved losses have replaced the losses formerly attributed to availability and quality. This is a good indication that future improvements should be more focused on a process upstream of this one. Note, while this chart can be very useful for engineering and management, it is less useful for line workers or others who do not have training in the definition or use of OEE. Also, this chart does not follow the strict Ford definition of OEE, because blocked and starved time is broken out and measured as separate components.

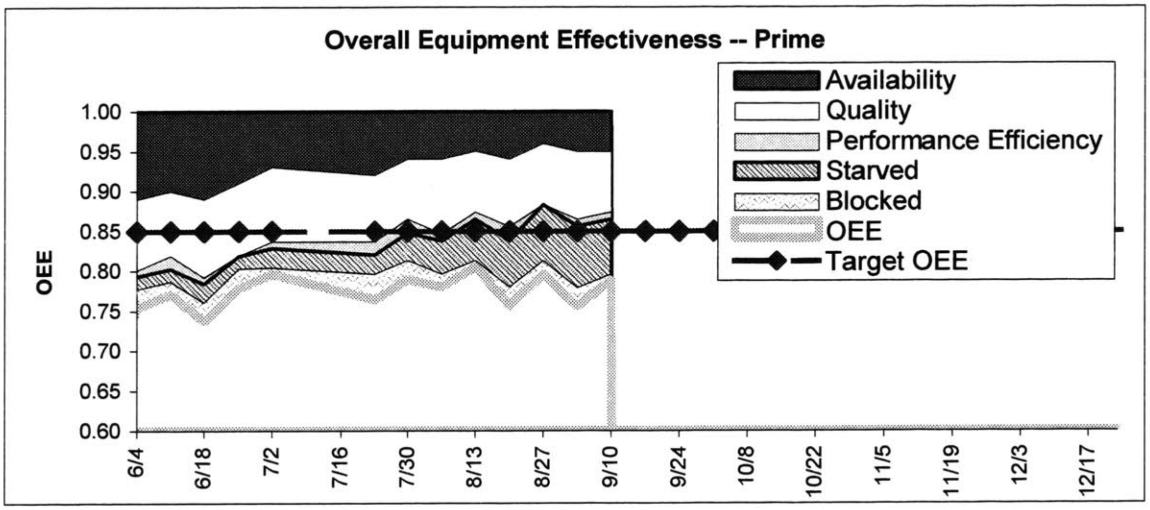

Figure 5.12 OEE Stack Chart

The trend of automation and manual downtime for each process can also be charted and reported, as well as daily quality percentages, so engineers or work teams can track the overall progress of any improvement efforts.

The OEE stack chart was developed during the internship, and subsequently began to be used by other departments in the manufacturing plant. As opposed to simply showing the OEE measure, this chart decomposed that measure into a level of detail that was appropriate for those using the chart.

5.6.3 Level I - Manufacturing Process Level

Production work teams can chart data of almost any relevance at Level I, from the total number or duration of line stops at each station, to the number of faults on a certain machine, to the number of occurrences of a specific quality problem that caused the line to be stopped, to a Pareto chart of the causes of quality defects. All of these could be important to total throughput, but the input of the team should be used to determine which measurements are worth the time to track. At KTP, the only information tracked by the work teams at this level were measurements that the team developed in response to specific problems or improvement initiatives.

5.6.4 A Note on the Use of Computers

A computerized tracking system, similar to that described in section 5.4, could be developed to have the capability to provide all of the charts and reports that are described in this section, which could then be printed and posted for those who would use the information. This would save the time that people would spend transferring the data and making the graphs. However, one must distinguish between the non-value-added process of making the charts and the value-added process of analyzing and reviewing the results. The problem is that if people are not forced to spend time doing the first task, they may not find the time to perform the second one.

Toyota has developed a certain reputation for not liking computers in the manufacturing plant, since computers tend to take away information from the guys on the floor and give it to only those with access to the computer terminal (Johnson, 1998, p.45). Even if information can be made available to everyone, the process of recording measurements and charting data forces people to understand the charts anduse them. Cassidy (1999, p.71) noted with regard to line workers that it should be a natural part of their job to record disturbances and measurements on charts or blackboards. The person who records data is inclined to analyze, and the analyzer is inclined to think of solutions. This logic can be applied to engineers, repair workers, or even managers who are forced to spend time working with measurements.

Computer systems are very useful in their ability to record detailed data, however, and a possible middle ground might be to use a data collection system to record the data during each shift, but rely on line workers, supervisors, and engineers to take the data at the end of the shift and record it onto a chart in their work area.

5.7 The Ford Production System and Kentucky Truck Plant feedback process

The Ford Production System places emphasis on information feedback, visual control, and communication in several elements of the FPS program, although some aspects of an ideal feedback system are lacking. The Kentucky Truck Plant, and specifically the paint department, has followed the guidelines of the FPS program, and has also gone beyond those requirements in some areas, most notably with electronic data collection and reporting tools.

5.7.1 Ford Production System

The Ford Production System requirements contain items that deal with communication and feedback in several of the eleven elements, although it is not something that is dealt with in an overall cohesive manner. Most of the focus is on using the FPS measurables to drive improvement efforts, using display and information boards in the plant to communicate performance, and reviewing plant objectives and performance with employees. The following FPS elements deal with some aspect of feedback:

In-Station Process Control Element
Use work group display boards
Use general information boards
Use Total Productive Maintenance small group activity boards

Work Groups Element
Use FPS measurables to track improvement progress
Provide real-time work group specific performance feedback

Managing Element
Plant objectives reviewed with work groups
Relevant measurables information is made available to employees
Information technology enablers to record process measurables

The FPS guidelines focus mostly on the charting and reporting aspect of feedback, communicating historical performance information via display boards. Some mention is made of real-time feedback, but what is meant by real-time is not well defined, and information technology is mentioned as an ideal way to track the FPS measurables. There is little mention of the use of andon boards or electronic displays, although this could certainly be considered to meet the requirement for real-time feedback. It is not clear what kind of performance feedback or measurables are "relevant" or "work group specific." There is also no mention of the role of the work teams in recording or charting this performance information. The idea seems to be that management possesses this information, and is responsible for communicating it to those who need to know.

One major weakness of the current FPS process is its reliance on the FPS measurables to be used at all levels of the organization to drive improvement. An early design goal of FPS was to have a common set of measures used by all levels of the plant (Kowalski, 1996, p.76). However, the FPS measurables like OEE, FTT, DTD, etc. 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 (Kowalski, 1996, p.68). Nonetheless, these metrics are typically reported to work teams and posted on their display boards. Welnick noted the same problem:

> FPS needs additional information at the hourly operator level. Currently FPS metrics are designed to give feedback to plant managers and upper executives on the progress of a plant. These measurables do little to provide feedback on performance to individual employees or units within the plant. A key element in developing improvement activities by small groups is continuous feedback on performance and more of this needs to be developed (Welnick, 2001, p.63).

DeJesus (2000, p.3) also observed that FPS measurables are solid at the macro level, but of little functional value at the local, implementation level.

One example with regard to throughput is the reporting of the OEE metric. The OEE of each process area is averaged over a one month time period, and several consecutive months are posted as a chart on the display board of the work team for that process area. In many areas, this was the primary feedback on throughput performance that the team received. OEE is often debated at Ford, for some important reasons regarding how it is to be used and whether it provides the proper incentives for improvement. However, the biggest problem with its use at the local work group level is twofold:

1. It couples together all of the different reasons for throughput loss, so it cannot be determined why the losses are occurring and improvement efforts on certain factors cannot be tracked to determine if they made an impact.
2. In a serial process like that in the paint shop, OEE often depends on factors outside the control of the team, such as blocks and starves.

Couple these two problems with the fact that OEE is reported in a monthly average, and it becomes almost impossible for a work group to use this metric to identify problems or track improvement efforts.

Kaplan (1989) made this example in the "Texas Eastman Company" case from Harvard Business School by using a bowling analogy.

> Suppose you were on a bowling team, only when you bowled, the alleys were completely blacked out and the only information you got after ten frames of bowling was the total number of pins your team knocked down. Wouldn't it be difficult for you to improve your game? Reporting a single, averaged number….is just as remote from one person's activity as the total number of pins hit over the course of an evening.

Metrics must be developed for use by the work groups to track items that directly affect the performance of the process, that are solely under the control of the work group, that decouple each of the Level I reasons for poor performance, that show directly whether improvement efforts had their desired effect. This information must be fed back quickly enough and in a manner that is useful in determining cause-effect relationships. This is not an activity that can be completely prescribed by the FPS program at Ford, but rather the FPS program should encourage the use of various methods of feedback, describe when certain methods are appropriate, and provide guidelines for determining what information a work group might find useful.

5.7.2 The Kentucky Truck Plant

KTP has implemented some of their own feedback processes that are not necessary directed by the Ford Production System requirements. System-level and process-specific andon boards exist in some areas of the plant, although these were not being used as much in the paint department. The paint area did make use of two types of andons. One was a large board that listed the number of jobs currently present in each area of the system, although there was no way to tell what number was acceptable or desirable. The second was a smaller board that listed the number of jobs in each of the three "strip" buffers, the areas after each paint oven, relative to the maximum these buffers would hold. These andons only showed the counts for the local buffers related to that specific process. Aside from andons, each process had an electronic sign that displayed the amount of time that the line was down due to stops by manual operators.

The most extensive feedback in the paint shop was developed using computer systems. Between the central plant computer system, a local database system in the paint shop, and a computerized quality defect recording system, almost any information regarding throughput (or any other aspect of process performance) could be obtained. Detailed fault listings, manual line stops, quality percentages for various model or color styles, production counts, buffer counts, and actual process cycle times were all tracked via these systems. Reports were available that summarized some of the data, such as quality or OEE data for a shift, although many reports were still being developed. Much focus was given during the internship to developing and refining this information system, ensuring that the data was accurate, complete, and reported in a useful format. However, this information was available only to those in the department who had access to a computer, and even then many floor supervisors and others were unaware of the level of information that was available.

In terms of charts and reports, the paint department made extensive use of SPC charts to track data related to various paint characteristics, since this was a highly variable process. A few work groups had developed their own performance charts to measure the progress of specific improvements they were working on. The department management also distributed a report to the work groups each week giving the overall production, quality, and safety measurements for the previous week, and describing any improvement efforts or changes that were taking place or needed to take place.

5.8 Production worker survey regarding feedback

As a part of the thesis research, fourteen randomly selected production workers in the paint shop were personally interviewed in order to determine how effective the KTP and FPS feedback methods worked in order to provide visibility of the system (to be sure people understood where problems existed) and useful specific feedback (to help specifically identify and solve the problems). Questions were also asked about the effectiveness of the work groups in solving problems, and the usefulness of FPS and other metrics that were currently being posted on the display boards. Details of the survey and some sample comments are contained in Appendix B. A summary of the results is included in this section.

5.8.1 System visibility

Having visibility of the performance of the overall manufacturing system in real-time was of surprising importance to most of the production workers interviewed, considering the minor emphasis that had been placed on ensuring that this information was available. What was most surprising was the level of tacit knowledge that existed among the workforce from finding ways to determine the status of the system. Most workers made use of the limited andon boards that existed, although the buffer counts were much more useful than the overall zone count reports. Many people also knew from experience that yellow or red lights in certain places signified that buffers were full, even though the intent of these lights was not necessary to communicate that fact to them. Most everyone also made use of an obscure computer terminal near the exit of the paint area that listed the number of jobs produced during that shift. Workers in one case even told about some people using sealer gel on the floor of a truck cab to write the number of jobs produced at a certain time, so others further along in the production process could see how well they were performing.

The workers clearly had a desire to possess this kind of information. Desire of this sort could be indicative of workers trying to satisfy higher-level psychological needs by determining if they were performing well, or simply a personal interest since lost throughput meant working overtime, but was likely a combination of both. As it was, the only defined way that all workers gauged their performance was with the announcement each day after lunch regarding the amount of overtime to be worked that day. Having possession of a wireless radio, or being in close proximity to someone who did, was desirable in order to be aware of problems in other areas of the department. Information also traveled through word of mouth, and most workers felt that if they asked how things were running, they could find out.

Some workers had the view that overall system performance was something that management specifically did not want them to know. While many knew that all the information was available on computers around the plant, some stated that they believed they were not permitted to access this information. In one area, an andon sign was not working, and one worker expressed the opinion that it was intentionally shut off, because "management wants to keep us in the dark."

About half of the workers made note of the report given to them each weak in their group meeting that described production, quality, safety, and other measurements for the previous weak. While everyone agreed that the report was valuable and that they were happy to have the information, many said that the feedback was delayed too long. "I would like to know at the end of each day how we did," stated one worker. "By the time next week comes, I won't even remember what happened today." Given the monotony and repetition of production line jobs, this seems plausible.

5.8.2 Usefulness of FPS metrics

Each work group has a team meeting area that contains at least one full wall of charts, data, FPS metrics, and other information related to performance. Two primary questions were asked regarding the usefulness of FPS metrics and other charts to the production workers. The first asked whether they personally understood what the metrics meant, and the second asked whether the team used them or paid attention to them. There were few affirmative answers to either question.

Each worker was asked about the OEE and FTT metrics. Persons who worked in the Enamel paint process, where FTT was measured extensively, had a good understanding of this measurement. Not one person could explain the full meaning of OEE, and only a few even knew that it was related to throughput.

There was a significant amount of data and charts that were posted on the display boards for each work group. Very little of this information was used by ordinary members of the work groups. Some mentioned that they paid attention to the information on overall warranty claims related to paint, and to items related to safety and overtime hours. Many said that they believed their team leaders or members who had been through FPS training were more versed in the meaning of certain charts. Several reasons were given for not using the charts, including lack of training regarding their interpretation, the complexity of the charts, lack of information specific to their process, operation, or crew, and occasionally unwillingness of specific people to get involved.

5.8.3 Useful specific feedback

This seemed to be the biggest area that was lacking for the production workers. Information that was relevant to their performance, such as downtime and quality, were not always charted over time to show trends. The data that was charted was of too high a level, and too disconnected from the work of individual people. The problems workers talked about were similar to those described by Kowalski, Welnick, and DeJesus in other Ford facilities working with FPS. The most useful charts for most groups were ones that they developed on their own, to track specific improvements they were working on.

Paint sprayers, specifically, had no means to gauge whether they were performing their job correctly, since there was no real-time feedback regarding defects. If there was a major problem, a supervisor might actively communicate the issue to a few people to get it resolved, but there was no passive means for this feedback to occur. Weekly, the work groups had a chart that was posted in their meeting area that listed the types and number of defects recorded over the previous week, but there was no way to determine what operation produced them, or even whether it was due to manual or automated processes.

One worker in an inspection area described what he saw as a natural tendency of people to deny to themselves that their actions create defects. The monotony of production line jobs can tend to make even the most conscientious workers produce defects without even noticing. He related:

> A superintendent took me off the line one time to show me a defect that I had not caught. It looked terrible; the whole tailgate was painted thin. It was obviously a defect. I told him there was no way I could have missed that. It wasn't that I was afraid of getting written up, I truly didn't believe that I could have missed such an obviously bad defect. We looked up the tracking history on the truck, and sure enough, I was on the job when it was inspected. I learned that no matter how much I try, I'm human and make mistakes. Other people won't learn the same lesson until you can show them without a doubt that they cause defects despite their best efforts not to.

This kind of learning is key to involving workers in developing mistake-proofed and robust processes that overcome human fallibility. Other workers separately agreed with the need for a system that promotes individual accountability, or at least team accountability. "As long as someone can blame a problem on someone else," one said, "they will."

What was somewhat surprising was that many workers wanted this feedback for themselves. A repair worker was frustrated because he had no way to tell if a truck being repaired had been repaired previously, if it was for the same defect, and if it was his fault that the defect was not fixed properly. A paint booth sprayer suggested that real-time quality results be displayed for each of the two Enamel paint booths, so workers in each booth could compete against each other. He said that people care more about their fantasy football leagues, because they can see their performance and compete against others. Another suggested that more feedback be split between work crews, so the crews could compete against each other.

Most workers said that the only direct feedback they received would come from a supervisor, and it was mostly negative feedback if they performed extremely poorly. "People like to get feedback when it's good and bad, so they can judge for themselves how they are doing," noted one paint sprayer.

5.8.4 Effectiveness of work groups

In general, most workers thought that work groups and coordinated work group meetings were a good thing, although there was some debate over their effectiveness in solving problems and driving improvements. The improvement efforts of most groups focused primarily on issues that were important to the workers, in areas such as safety and morale. Quality problems were often addressed, but most of these were problems due to other processes or other departments.

Production workers were somewhat reluctant to suggest changes that could eliminate jobs or increase the workload of existing workers. Even line balancing activities were opposed by some workers. One team leader noted, "You have to draw the line somewhere. I don't want to be responsible when people lose their jobs." This may be an issue related to cultural norms in the group that prevent people from bringing up suggestions like these in team meetings. By contrast, when one process area was being redesigned, several representatives from each work crew met with engineering personnel to come to a consensus on design issues. This group suggested, and financially justified, an idea for automating one operation that would have eliminated four production worker positions on the line (two of which were rather difficult jobs)[13]. It is clear that workers will not blindly resist design changes that result in the reduction of labor.

Workers were frustrated with their inability to get changes and improvements done. When they made note of problems that needed fixed, they were rather quickly addressed. However, when a group suggested a change or improvement that could be made to the process, it was much harder to get the change to happen. Any change that affected the standard work at each job, work tools, or ergonomic issues had to be approved by the teams from all three work crews, as well as by management. This was frustrated by the fact that there was no designated time or method for workers from all three crews to meet together. Some stated that it was difficult to get all but the simplest changes passed. Even if everyone could be convinced that the change was worthwhile, management had to commit money to it. Some workers thought that each group should have a small budget to make their own changes.

While it may seem odd to spend money on changes that do not affect the performance of the system, it can still be advantageous. Johnson (1998) notes that often workers focus on improving things that are important to them, not to the plant, but that is acceptable because they are learning to improve. If they can learn to use the scientific method in making improvements of any type: define the problem, develop hypotheses, conduct experiments, and use feedback to judge the hypotheses, then they can apply those skills to bigger improvements and bigger gains.

5.9 Suggested changes to Ford's feedback process

5.9.1 System Visibility

Ford, via FPS and changes at the plant level, should place more emphasis on the use of feedback devices that promote system visibility in real-time, such as andon boards and real-time

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[13] There were other positions in the plant that these workers could transfer into, which may be one factor that reduced the reticence of the workers.

electronic displays. At the same time, high-level metrics like OEE should be removed from the information reported at the work group level. Historical numbers and trends for metrics related to system visibility, like throughput and overall quality, can still be reported at this level, so long as the groups understand the meaning of the metrics. Gradually, as the level of understanding by production workers grows, higher level metrics can be added to those reported to the work groups.

5.9.2 Level I Feedback

Some substantial improvements are required to the manufacturing process level feedback that is typically directed toward the production work groups. The first step should be to ask precisely what kind of measurements the work groups feel they need in order to understand where problems exist in the process. Some of these may not be able to be practically measured, but many will. These should then be added to, with process-specific metrics related to throughput from Level I of the decomposition in chapter 4, plus process-specific metrics related to quality, cost, or other factors of importance.

The next step is to determine what feedback method is most appropriate for these measurements. Real-time displays should be used for information that requires a quick response or whose root cause is transient in nature and not fully understood. On-demand electronic data may be useful for the raw data collection related to these metrics, but charts and reports will probably constitute most of the remainder of the feedback. Any information technology system that is developed to track Level I metrics should be designed in a bottom-up fashion, focusing on the feedback needs of the production team members. This will aid in the acceptance of the system, as well as maximize the productive use of it.

Detailed feedback information should be introduced gradually, with time taken to explain the meaning and proper interpretation of each metric to the work group. At that point, the work group should take over ownership of tracking and charting the various metrics specifically related to their process. This will promote understanding of the feedback, and prompt workers to analyze the data as they are charting it. An electronic system can be used to collect the raw data, to make this task less tedious.

5.9.3 FPS Measurables

The FPS measurables, such as OEE, FTT, DTD, BTS, etc., are acceptable metrics the manufacturing plant, so long as those who use them understand their meaning and have full control over their outcome. These are the reasons that these metrics are inappropriate for use at the work group level. They are not inherently bad, just incomplete for use at a detailed level. They can and should still be used at the analysis level (by engineering, middle management, etc.).

One of the primary uses of these metrics may be to evaluate the effect of major system improvements, such as redesigned processes, changed buffer sizes, more reliable equipment purchases, or overall new system design. They are not complete for this purpose, since things like floor space, labor, and labor efficiency are also factors to be considered. However, if a monetary value can be put on an incremental reduction in dock-to-dock time, or an improvement in OEE or FTT, then major projects can be better evaluated as to their benefit in advancing the manufacturing system toward the lean ideal.

5.10 Dangers of electronic feedback

A word of caution is in order regarding the use of computer-aided data collection and reporting of performance metrics, since Ford and many other manufacturing companies have placed a high priority on developing information technology systems of this type. These systems can generate large benefits in collecting and making available data that previously could be collected only through tedious manual effort. This information can be analyzed, correlated, and reported fairly quickly, in virtually real-time, and can be made available on a computer terminal in a manager's office. It is no wonder that the development of IT systems of this type has been given management's support in many plants. However, there are serious risks to this approach.

Toyota's view is that information belongs in the hands of people on the floor, and that managers should "go and see" when they want to determine performance. There is an intangible benefit to having production workers involved in tracking measurements. The risk of completely automating the system may transform the feedback process from a control system to just another tracking system (Stec, 1998, p.72). Additionally, if workers are asked to generate data that are only useful to, or only used by, managers and supervisors, it is unlikely that the data will be extremely accurate.

More importantly, however, there is a risk that production workers will view an automated tracking system as a means to monitor their every move. A "big brother" will be constantly watching them and have enough detailed information to punish them for any mistake they might make. Delisle (2001, p.37 & 44) observed a similar problem when implementing a computer system to record and display defects in an automotive body shop. Inspectors saw the new system as a possible disciplinary tool to be used by management to reprimand inspectors who did not properly repair defective jobs. Additionally, the system could be used to monitor what inspectors were doing during the shift, and compare their speed and performance to other inspectors and other shifts.

Several studies have found that electronic monitoring makes jobs seems more stressful. This may not happen because of the monitoring, per se, but because of other changes that accompany the introduction of the new observation method (London, 1997, p.166). Chalykoff (1987, 1988) performed extensive study of employee response to electronic monitoring in clerical office jobs, and noted that the immediate consequence is a perception of "close supervision." In general though, employees noted that the monitoring was neither good nor bad in itself, but its acceptance depended on how supervisors approached it. Management could choose to use the information in a harsh or supportive manner, using it to control workers or help develop them.

When supervision used the monitoring for support and development, workers seemed to think that it was beneficial overall, since computer-collected data made the basis for evaluation less subjective.

This research emphasizes two things. First, involving workers in the reporting and charting of performance data will help to foster the notion that the feedback is for the benefit and development of workers, and not for control or discipline. Second, supervisors should be trained in the proper and improper use of electronic data. While rare disciplinary use may be appropriate, appropriate restraint must be exercised in order that workers do not fear the system. The benefits of the electronic system can only be realized if workers trust that they have nothing to fear from using it.

5.11 Feedback System Summary

The feedback system described in this chapter can facilitate the improvement of throughput and many other operational objectives in the manufacturing plant, by providing the link in the control system so workers at all levels are able to close the gap between the desired and actual output. It meets the requirements defined in section 5.1 for an effective feedback system:

1. It is data driven. The feedback is based on quantifiable metrics at most levels, which can be measured automatically and reported in an unbiased manner.
2. It is timely and local. The decomposition approach, combined with increasing feedback frequency at lower levels, provides feedback that is sufficiently detailed and relevant at each level of the organization.
3. It allows everyone to become a "problem-solver." Because everyone has access to the knowledge of their performance and the system's performance, everyone can become involved in closing any gaps in performance.

4. It aligns the organization toward achievement of the same goals. Because each level of feedback corresponds directly to the higher-level metrics, the entire organization is aligned, even though the metrics used are not the same.
5. It aligns authority with responsibility. Each level has a sufficient level of detail that allows them to discern and decouple those issues which they can control from those which they cannot.

Chapter 6: Conclusions and Recommendations

This thesis described a number of aspects of manufacturing system design and improvement that are related to production throughput, as experienced in an automotive paint system at Ford Motor Company's Kentucky Truck plant. The Ford Production System, Ford's manifestation of lean manufacturing, was also discussed, specifically its relationship to the throughput improvement efforts.

The first issue explored was the analytical methods that could be used to model throughput in a manufacturing system and locate the most prominent throughput bottlenecks. Empirical, mathematical, and simulation-based approaches were considered. Second, a design decomposition was constructed using principles of axiomatic design that describes the requirements for a system that produces at takt time. The design was categorized into three levels based on amount of detail, and metrics were proposed for each level. Third, the issue of performance feedback was explored, showing how a manufacturing system and organizational system might be better constructed to facilitate problem-solving and improvement efforts by workers at all levels of the organization. Conclusions and recommendations for each of these issues are described in the following sections.

6.1 Throughput modeling and bottleneck analysis

Several throughput analysis techniques were described and critiqued for their accuracy, effectiveness, and practicality in the automotive paint system.

- **The Ford KTP paint department should make use of both the Cassidy approach and discrete-event simulation for throughput modeling and bottleneck analysis.**

Ford's Capacity Analysis Procedure that is referenced in the FPS literature was not appropriate for use on the paint system, and is probably not accurate for many other similar manufacturing systems. Empirical approaches such as flow monitoring were found to be prone to error or imprecision. Mathematical approaches were advantageous because of the calculation speed, but suffer from a lack of ability to handle complexity due to reentrant flow or multiple part types. The Cassidy approach provides a means to analyze the causes of throughput loss for one shift, using a minimal amount of data. Simulation performs a more complex throughput analysis, and can be used to consider the effect of improvement scenarios, design changes, etc.

- **Ford should work to develop improved guidelines for throughput and bottleneck analysis, and possibly develop or purchase a mathematical or simple simulation-based software package that can be used in manufacturing plants for throughput and bottleneck analysis.**

Ford's current bottleneck identification procedure did not work for the paint system, and likely would not be accurate for many other manufacturing systems. GM's use of the C-More mathematical tool has been shown by Cassidy, Longcore, and Schulist to be very effective in performing throughput analysis in various automotive manufacturing environments, despite the fact that it cannot handle every detail of complexity. While this may not be as useful to the paint department, it could provide substantial benefit in other areas. An alternative is a simple commercial simulation package that requires minimal training to use. The throughput simulation for this project was constructed using Automod software, which is probably more complex than necessary in most cases. A simple package like Process Model may be more appropriate. All the work involved in throughput improvement is useless if the proper bottlenecks are not identified, and Ford should help to ensure that this does not occur.

6.2 Throughput Design Decomposition

The design decomposition looked at the requirements for a manufacturing system to achieve its takt time throughput, deconstructing the requirements into increasingly detailed levels.

- **Achievement of takt time throughput should follow a path dependent approach, so as to avoid problems inherent in the coupled design**

At the first level, the priority should be first to minimize lost throughput, and only then to use process overspeed to overcome those losses. Additionally, the causes of lost throughput should be fully understood before process overspeed is increased, since this could result in additional throughput loss if manual or automated operations are constrained for cycle time. At the second level, improvements to quality should take priority over improving process uptime, since quality improvements will improve throughput but also reduce the number of line stops due to the detection of defects. In addition, quality, uptime, and cycle time improvements should be prioritized over the increase of buffer sizes when trying to reduce blocked or starved time.

- **Specific attention should be paid to ensuring that it is possible to measure, or at least observe, the uncoupled performance of the functional requirements at each level in the decomposition.**

Metrics were proposed for most of the requirements, where it was practical to record or track them. Even if measurements are not formally recorded for each element, it should be kept in mind when one metric may contain more than one dimension of performance, and some attempt should be made to at least observe the effect of each dimension separately.

6.3 Performance Feedback

Performance feedback was presented as essential to building an environment where workers at all levels of the organization can understand the problems, learn what affects performance, and participate in improving the system. While creating this environment is not a sufficient, it is a necessary condition for the creation of a learning organization. Several recommendations can help foster this.

- **Performance feedback, and the development of feedback metrics and methods that are useful to each level of the organization, should be given more focus within the Ford Production System.**

The primary goal of the Ford Production System should not be to prescribe a pre-planned solution for manufacturing system improvements, but rather to encourage the evolution of the organizational culture toward one of continuous improvement, learning, teamwork, and empowerment. The core abilities that are required are to 1. Understand the ideal state of a manufacturing system that meets its requirements with no waste, 2. Receive performance feedback that is detailed and specific enough so that each person can understand why the current state does not match the ideal state, and what part of that gap he or she contributes to, and 3. Apply the scientific method, continuous learning, and team problem-solving toward closing that gap. Building this foundation will facilitate the implementation of "lean" tools and methods, as people begin to see why they are currently the best solutions available to close that gap. In addition, this environment may result in the development of innovative ideas that even the FPS designers could not have conceived. None of this can happen without a good system of feedback.

- **The FPS group should work to develop guidelines for the development of process-specific feedback that is useful to production work groups, considering the feedback method and feedback delay that is most appropriate.**

Each work group is different, each process is different, and each set of problems faced is different. FPS cannot prescribe the feedback that is most appropriate, but can coach people regarding how to determine this on their own. The requirements are that any measurements be at a level of detail that ensures that the team is fully in control of the measurements, but also that the measurements correspond to higher-level metrics of the system. Feedback frequency should depend upon the need and desirability of responding quickly to deviations in performance. Issues that require quick feedback to identify the root cause, or that need to be corrected quickly to prevent significant waste, should be communicated through real-time feedback where possible, whereas issues that cannot or do not need to be resolved immediately can use less complex feedback with a longer delay.

- **Remove all but the most basic high-level metrics from the feedback for production work groups.**

Having too much information that is complex or not understood can hinder the use of data by work groups. Boil the information down into a simple form, and give the groups more information as they request it or require it.

- **Introduce new feedback metrics gradually, taking the time to explain each one to its recipients and allowing them to absorb it before proceeding further.**

As stated before, the primary purpose of feedback is to promote learning that will help eliminate deviation between actual and desired results. If people do not understand the feedback, it is not useful to facilitate learning. This can be applied not only to work groups, but also to engineers, supervisors, and others in the organization.

- **Involve production and maintenance workers in the charting and reporting of performance measurements, even if computers are used to gather the raw data.**

Those who record are inclined to analyze, and those who analyze are inclined to think of solutions and improvements. Assigning this task to production workers may mean that paid time must be allotted at the end of each shift for this activity, but it could be five of the most valuable minutes someone spends all day, if the recording results in understanding and learning. Ford should resist the inclination to allow computers to completely take over the job of tracking and reporting performance.

- **More use should be made of real-time feedback displays such as andon boards to promote system visibility.**

In order to see themselves as part of the whole manufacturing system, and understand their effect on it, everyone must be able to passively discern the status of the system at all times. Electronic displays are not inexpensive. This may be a difficult recommendation to justify financially, since it is typically difficult to quantify the benefits of a cultural change to the organization.

Manufacturing supervisors will need to be trained in the proper and effective use of electronic monitoring and feedback of production workers.

Electronic monitoring of individual actions can save enormous time in tedious data collection, and might even be appreciated by workers as a more objective means of evaluation. However, the danger is that a system like this could be used solely to control, monitor, and discipline workers instead of being used to foster their growth and development. If workers perceive the former is the case, they will be likely to resist any use of the feedback for their own benefit. It may be necessary to prohibit altogether the use of electronic feedback for disciplinary purposes, or at least stay generously on the side of caution. Otherwise, the very tool put in place to facilitate the culture change may instead work to undermine it.

Appendix A: Accounting for the Variation of Workstation Cycle Time

Several instances of lost throughput in the Ford paint process were due to variation in the work content between different vehicle model styles. A heavy-content model may require more than the line cycle time (or takt time) for a worker or robot to complete the job. This time can be made up during low-content models, so the average is still less than the line cycle time. However, the operation must be designed so that the operator or robot can fall behind and catch up without disrupting the production flow, either by increasing the station width in an assembly-line process or by decoupling the station from adjacent stations.

One way to eliminate this problem is to design every operation and process to be capable of producing only the heaviest-content jobs. In many cases though, this would result in an enormous waste of resources and low manpower efficiency.

Another solution is to distribute the various models as evenly as possible over the production time. This will minimize the problem, but not eliminate it. Additionally, reentrant flow in the paint system rearranges the production sequence so as to make it unpredictable.

This appendix describes an analytical method that could be used to determine an optimal station width or optimal amount of decoupling so that process disruptions due to model mix can be prevented to a desired service level. The method assumes that models arrive at a station based on a defined binomial distribution, meaning that production of the various models is distributed over the production time, but the units arrive in no pre-defined sequence. The first section walks through the steps using an actual example from the Ford paint system. The second section describes the general algorithm that could be used to create a software tool for use in process design.

Specific Example

Step 1: Input the parameters that describe the operation work content, line time, and % of mix for each model style. Work Content is the time spent from the start of that job to the operator or robot being ready for the next job. Line Time is the time from the start of that job until the start of the next job arrives at the same point on the assembly line. The Line Time differs in this case since a crew cab is longer and takes up more space on the line. In other cases, the work content was fairly consistent but the line time was highly variable (since some cabs were followed by boxes but others were not). The line speed is necessary to calculate station width if the operation is performed on a moving conveyor line.

Model Style	Work Content (sec.)	Line Time (sec.)	% of Mix
Crew Cab	55	46	50%
Super Cab	42	45	16.7%
Regular Cab	30	44	33.3%
Line speed (ft/min)	20		

Step 2: Check to be sure that the average work content is less than the average line time for the given mix. If this is not the case, the operator or robot will not be able to keep up with the work regardless of the variation. The station width corresponding to the average line time is calculated here as well.

Average Work Content (sec.)	44.5
Average Line Time (sec.)	45.2
Average Station Width Used (ft.)	15.1

Step 3: Determine the number of sequential units to consider. This determines the level of refinement of the calculation. Since this model assumes that each job arrives according to an independent binomial distribution, but the cycle time overage is additive between jobs, the total cycle time overage is a random walk and therefore stochastically indeterminate. However, in the paint manufacturing system the arrival distribution for each job is not fully independent. An

above-average number of crew cabs during one time interval makes it more likely that there will be a below-average number of crew cabs during the next time interval. "Regression to the mean" is more the norm, since the total mix of jobs is fixed over a long period of time. Therefore, this analysis method should be able to be used with reasonable accuracy.

The selection of the number of sequential units is a trade-off between accuracy and calculation intensity. For this manual calculation, batches of five jobs will be considered. Using a computer program to determine the possible combinations will allow larger batches to be considered.

Step 4: Determine all possible combinations of jobs that could make up a batch of size defined in step 3.

Step 5: Determine the cycle time overage (or underage) that would result from each of the possible combinations.

Overage = #Crew*(Crew_Work Content – Crew_Line Time) + #Super*(Super_Work Content – Super_Line Time) + #Regular*(Regular_Work Content – Regular_Line Time)

Step 6: Determine the probability that each combination might occur. There are three possible model styles, so the probability formula is:

Probability = Combin(C+S+R , S) * Combin(C+R , R) * [P(C)^C * P(S)^S * P(R)^R]

Where C = #Crew, S = #Super, R = #Regular, and P(n) = % of that model in the mix

The results of steps 4, 5, & 6 are shown in the next table.

Step 7: Arrange the various combinations in order of decreasing cycle time overage, and drop those that result in a negative overage. The first negative overage is kept for reference.

Step 8: Determine the station width or decoupling required to accommodate each cycle time overage, and calculate the cumulative probability / service level associated with each one.

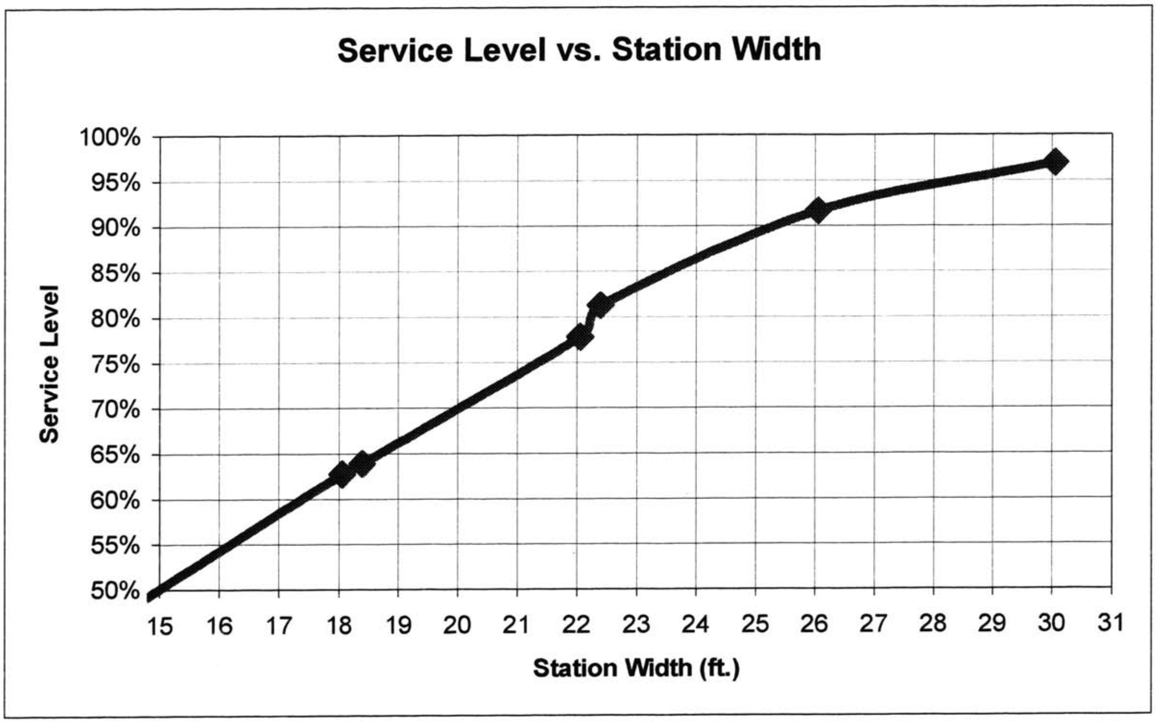
The cumulative probability is simply the sum of the current and all prior individual probabilities. The service level is (1 – Cumulative Probability).

Crew	Super	Regular	Cycle Time Overage	Probability of Occurrence
5	0	0	45	0.03125
4	1	0	33	0.052083333
4	0	1	22	0.104166667
3	2	0	21	0.034722222
3	1	1	10	0.138888889
3	0	2	-1	0.138888889
2	3	0	9	0.011574074
2	2	1	-2	0.069444444
2	1	2	-13	0.138888889
2	0	3	-24	0.092592593
1	4	0	-3	0.001929012
1	3	1	-14	0.015432099
1	2	2	-25	0.046296296
1	1	3	-36	0.061728395
1	0	4	-47	0.030864198
0	5	0	-15	0.000128601
0	4	1	-26	0.001286008
0	3	2	-37	0.005144033
0	2	3	-48	0.010288066
0	1	4	-59	0.010288066
0	0	5	-70	0.004115226
0	0	5	-70	0.004115226

Crew	Super	Reg	Cycle Time Overage	Probability of Occurrence	Cumulative Probability	Service Level	Station Width Req'd (ft.)	Job Decoupling Required
5	0	0	45	0.03125	3.1250%	96.8750%	30.1	1.00
4	1	0	33	0.0520833	8.3333%	91.6666%	26.1	0.73
4	0	1	22	0.1041666	18.7500%	81.2500%	22.4	0.49
3	2	0	21	0.0347222	22.2222%	77.7777%	22.1	0.46
3	1	1	10	0.1388888	36.1111%	63.8888%	18.4	0.22
2	3	0	9	0.0115740	37.2685%	62.7314%	18.1	0.20
3	0	2	-1	0.1388888	51.1574%	48.8425%	14.7	-0.02

Step 9: Graph the Service Level vs. either Station Width or Job Decoupling. Select a station width or decoupling level that corresponds with an appropriate service level. For this case, a station width of 25 feet results in a service level of about 90%. 90-95% service level should be

appropriate in most cases. As can be seen in the graph, designing the station with the average width of 15 feet would result in a process disruption more than 50% of the time.



General Case

Step 1: Input Parameters.

Number of model styles	Num_Styles
Name of each model style	Mi
Work content for each model style	WCi
Line time for each model style	LTi
% mix for each model style	P(i)
Line speed (if assembly line process)	Linespeed

Step 2: Check to be sure that the average work content is less than the average line time for the given mix. Also calculate average station width used for average line time.

Average Job Content = Sum (WCi * P(i))
Average Line Time (Av_LT) = Sum (LTi * P(i))
Average Station Width = Av_LT / 60 * Linespeed

Step 3: Input # of sequential units to consider. This could be done in step 1.

# of sequential units Num_Seq

Step 4: Determine all possible combinations of jobs that could make up a batch of size defined in step 3. Build a binary array with (Num_Styles) dimensions, each dimension of size (Num_Seq). Set each element of the array as 1 or 0 if the element represents a valid combination of jobs totaling (Num_Seq).

Binary array A(i, j, k,…,n)

If i + j + k +…+ n = Num_Seq, then A(i, j, k,…,n) = 1
Else A(i, j, k,…,n) = 0

Step 5: Determine the cycle time overage (or underage) that would result from each of the possible combinations.

For each element of the array where A(i, j, k,…,n) = 1:

Cycle time overage (CT_Over(i, j, k,…,n)) = I * (WC(1) – LT(1)) + j * (WC(2) – LT(2)) + k * (WC(3) – LT(3)) +…+ n * (WC(Num_Styles) – LT(Num_Styles))

Step 6: Determine the probability that each combination might occur. The general form of the binomial distribution must be used to account for the variable number of model styles:

For each element of the array where A(i, j, k,…,n) = 1:

Prob(i, j, k,…,n) = Comb((i + j + k +…+ n) , (j)) * Comb((I + k +…+ n) , (k)) *…*Comb(i + n) , (n)) * (P(1)^i * P(2)^j * P(3)^k *…* P(n)^n)

Step 7: Arrange the various combinations in order of decreasing cycle time overage, and drop those that result in a negative overage.

For each element of the array where A(i, j, k,…,n) = 1:

If CT_Over(i, j, k,…,n) <= 0, then A(I, j, k,…,n) = 0

Find the maximum of all elements of CT_Over. Rank(i, j, k,…,n) = 1, & A(i, j, k,…,n) = 0
Repeat, setting Rank = 2, 3, etc. Until all elements of A = 0.

Step 8: Determine the station width or decoupling required to accommodate each cycle time overage, and calculate the cumulative probability / service level associated with each one.

```
Station_Width(i, j, k,...,n) = CT_Over(i, j, k,...,n) / Av_LT * Linespeed
Decoupling(i, j, k,...,n) = CT_Over(i, j, k,...,n) / Av_LT

Find Rank(i, j, k,...,n) = S   (S = 1 to large#)
Cum_Prob(0) = 0
Cum_Prob(S) = Prob(i, j, k,...,n) + Cum_Prob(S-1)
Service_Level(S) = 1 – Cum_Prob(S)
```

Step 9: Graph the Service Level vs. either Station Width or Job Decoupling.

```
For S = 1 to large#
Find Rank(i, j, k,...,n) = S
Plot Service_Level(S) vs Station_Width(i, j, k,...,n)
Plot Service_Level(S) vs Decoupling(i, j, k,...,n)
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Appendix B – Production Worker Survey

The purpose of the production worker survey was to determine the level to which production line workers were aware of their own performance and the paint department's overall performance. The survey also attempted to determine what tools used by FPS and the KTP Paint Department were useful in helping production workers identify and resolve problems.

Fourteen production workers in the paint department agreed and were available to complete the survey, which done via a personal interview. These workers were randomly selected from a list of all workers in the paint department, and represented workers from all three crews and from all seven production teams within the department.

Following in this section are the survey questions, as well as notes (in italics) from the workers' answers. Repeated comments are only listed once.

Problem Identification and Resolution Survey

Kris Harper, Leaders for Manufacturing Intern
Ford Motor Company Kentucky Truck Plant CLT Paint Dept.

Background

Name (optional)

Team/Crew
Clearcoat / B; Polish / C; Polish / C; Tutone / C; Prep / C; Prep / C; Clearcoat / C; Misc / C; Clearcoat / A; Clearcoat / C; Basecoat / C; Basecoat / A; Tutone / A; Misc / A

Job Description
Sprayer; Sander; Sander; Repair/Mask; Sander, Sander, Sprayer, Misc, Sprayer, Sprayer, Sprayer, Sprayer, Repair, Misc,

Yrs at Ford
6, 7, 6, 6, 9, 8, 7, 6, 7, 6, 7, 7, 25, 8

Identification of Line Performance

Can you tell, throughout the day, how well your line is running, with respect to quality & delivery?
Yes, but there is no feedback for total downtime
Quality is pretty easy to tell, but some stations are kind of isolated
You have a better idea at the final station where inspection results are entered into the computer
Sometimes, not exactly but you may have a general feel
Yes, generally
I could guess
Generally no

If so, how can you tell? What do you use to judge this?
Feedback from inspection to paint happens after 40 minutes
Our team leader sometimes watches the inspections
If the line is not stopping, things are going well
Supervisors tell us if something is bad
Supervisors announce the line time (overtime) after lunch, which is usually determined by the number of jobs in the stacker (AS/RS), but it doesn't always make sense
Strip counts are available, but aren't always used
Inspection has access to tally sheets for quality
There is a computer screen at Polish that has production on it
Inspection leaves the hood up if the job is good. I can see if a lot of trucks have hoods down
If there are jobs in the strip, but none coming to our repair booth, that's good
If the supervisor is around, that's bad
I could ask the team leader or supervisor for the job count if I wanted to
The manual downtime is on an electronic sign. If you know what is normal, it's obvious when it's bad
A yellow light flashes when the basement (buffer after prime scuff) or prime strip is full.
E-Coat Scuff can see if a lot of Prime reruns are coming through
Sometimes the Sealer guys write the job count and time with sealer on the floor of the truck
You can see if skips come through the line, but on E1 it could mean that there are few repairs
We used to have the Enamel strip count on the signboard, but management doesn't want us to know anymore
We can only see Enamel quality in the weekly report
The computer at the shop entrance tells strip counts
At Hang you can see the yellow light at Unhang when the E-Coat strip is full
There's a red light when the Phospate chain stops because of a machine
We sometimes see quality problems from upstream
I could ask a supervisor
Paint booth operators have radios, they can hear if there are problems

When line stoppages or breakdowns occur on your line, do you always know the reason? How can you tell?
Talking to others
Booth operators and team leaders have radios
Only if the problems are recurring
If I look at the tally sheet

It depends which station I'm working at
I know if my partner on the other side of the truck has problems, but not other stations
There aren't too many reasons why we stop, so everyone pretty much knows why when it happens
Usually it's because they gave us a loaner
We usually rotate through all the jobs, and the basic problems don't change, so it's pretty easy to tell
Hearsay
We call the monitor room if there is no obvious reason why we're stopping
We can't always tell what's going on with the booth operators
We're pretty close together in the paint booth, so you can tell
Inspection doesn't always write up all the defects, just the main one
The computer tells us the number of times repaired, but not why or whether it was our fault
2-3 major faults happen all the time in our area

If not, do you ever find out the reason (later conversations, speaking with team leader, CIWG meetings)?
May be able to, if you wanted to know
Sometimes, depending on the supervisor

Can you identify the top 3 causes of lost production in your process (other than blocks or starves)?
Dirt, spits, thins, & doors opening
If we're rerunning jobs a lot
If I look at the tally sheet
Yes, loaners and no supplies
Unless we miss something, it's pretty obvious
Yes, pretty easily
Only if it's special problems
Only if it's your problems
Dirty chains & cycle time issues on some stations
If it's caused by manual operations, not automation
We stop a lot to fix other people's stuff
Doors closing, gun cleaning schedule not followed
No, we're off the main production line

Can you identify the top 3 causes of quality issues in your process?
We sometimes get them in our team meeting
Not properly sanding, missing defects
Marquee does not tell us if a second defect was missed the first time
Not specifically, unless there is a major problem
Not our problems, we see ones from upstream
Only if it's something specific that the supervisors tell us about
Can tell where defects are happening by where the repair trucks are being sanded
Wax inside doors, location of door guards
We hear if there has been an audit, or if the quality manager is looking at the line

What is your team doing to address these issues?

Fixing the door opening problem
We learn the top concerns in the team meetings
Trying to get the quality computer system to be used better
We work mostly on safety issues
Not much, some people don't care or try
The recurring problems come up in the meetings
We keep a log of the problems
Downdraft issues
We don't have a champion
Supervisors read a report in the weekly meetings
We tell them what we think the problem is and what we think they should do
Talk to our salaried champiom
Work on quality audit concerns

Do you know, each week and month, whether your process has met its quality, delivery, and cost requirements? How do you tell?
Supervisors tell us in the team meetings
SQDCM letters come to the meetings, but not many people are trained to understand them
I know if it's good or bad, but don't really look at the numbers
We get the warranty numbers in our meeting, and if stuff was caught by other departments
You can get numbers in the meetings if you ask
Sometimes, the supervisors are getting better about it
I think it is on the charts, but I don't look. Most charts aren't used
We know the overall quality numbers, but there is no team-specific feedback
The crew report summarizes SQDCM. The Crew Manager writes it. He cares, but most don't
Not really. Warranty numbers only show a problem if a dealer calls it in, but you rarely know what is really wrong
Measurement boards are updated weekly with overall quality
Sometimes the supervisors will go over it, but not always
Nobody has been to the class to understand the charts
No, most charts are for the overall department. Nothing is specific to our operations
Nobody ever explained what the charts mean
We only know if we don't meet them

Is your process improving its performance each week and month? How do you know? How do you judge this?
Volume is not improving, because the line time is not going down
It's tough to know. I guess it's somewhat my fault, because I don't ask
We have no metrics
It's tough to say about our process
The skids are getting cleaner. We came up with this and tracked it.
I think it's getting better.
Teams should update the charts, so we'd know what was on them and they would get updated more often
I have no idea
The team had no input on what charts were put up
The charts aren't specific enough to tell if our process is improving
The charts are there, but no one looks at them
There is no way to tell

Do you know when there were problems with your process on other crews? Do you know immediately?
We may hear from supervisors, if it's a big problem
It is not mandatory, we must ask the supervisors. If it's important, they'll tell us
We need an easier way to communicate previous shift defects to everyone
The team leader has email, and can send a message to the other team leaders
Team leaders leave notes sometimes
Supervisors meet or email
Only if I come in early and the previous shift is still here.
You usually know what line time they ran
Team leaders sometimes come to other crew's team meetings on their off-shift
You might talk to people in passing
No, it would be helpful if we did
Not often
Not unless it is serious
We'll hear gossip
We'll know about major medical problems or major downtime

Identification of Department Performance

Can you tell, throughout the day, how well the department is running? If so, how can you tell? What do you use to judge this?
Informal feedback from team leaders or the booth operator with a radio
Just verbally. Feedback is slow
We're at the end, so if we're not getting trucks, something is wrong
Somebody should communicate all defects
Just hearsay, because people want to know the line time
It's good if you have a radio
We can tell if the basement is full
Yes, because I've been here 8 ½ years. Others would have to ask or look for backups
There is a computer by Wax that tells how many jobs left the department
The computer in some areas can tell you
The big marquee boards give the number of trucks in each area, but they're not in good locations
The computer can tell the strip counts and the number in the stacker
The computer at Unhang tells what went through for the day, but you must look at the beginning count to know the shift count
Only if we ask the supervisors
The big marquee gives all the area counts, if you know what is normally
If there are a lot of repair jobs in E1 that is bad
We can look out the window at Prime
We may go to an early lunch if it's bad
The booth operators sometimes spread the word
Team leaders know. They tell us if it's major
Skips in the line are bad

If the department is not running well, can you tell in what area is the problem? If so, how can you tell? What do you use to judge this?
Mostly you can tell from radio talk
Not if it is outside our area
Just from obvious signs
The strip count signs and yellow lights in certain areas
From the big marquee
Just if a team leader tells us
The big marquee or the computer
We can tell that there is a problem, but can only tell where by hearsay
Supervisors may tell us
Ask the supervisor

Can you tell what the line time will be for the shift? Does it usually make sense to you?
If I can see the stacker count. Under 200 means we'll have a long day. If it's too high, Trim must be running bad
No, it doesn't always make sense. It doesn't always depend on the stacker count
Management doesn't want you to know, so you don't second-guess them
The strip count signs don't work
Yes, pretty easily, but I don't understand why we'll work overtime but only paint 20 trucks in the last hour
We try. Some guys can tell, but it also depends on how the previous shift ran and we rarely know that
It depends on what Chassis runs, but we seem to always work overtime
No, we usually guess high. It's obvious if it's really good or really bad

Is the department meeting its requirements? How do you know?
Not for volume, because we always run overtime
We get some quality and warranty feedback in our tea m meetings
We didn't get a report in our meeting this morning, so I don't know
I could get the stacker count if I wanted to
You can see the total jobs leaving the shop on the computer panel after Blackout
The supervisor gives us a report in our team meetings 9/10 times. I don't know where it comes from
I work in the Enamel booths. We are the department
We know if warranty claims went up or down, but other stuff only if the supervisors tell us
The crew manager does a report that we get in each team meeting
We know where certain problems are

Is the department performance improving each week and month? How do you know?
We know day to day, but not each week or month. I could probably get it if I asked
No trends are given to us
They tell you if it's bad
Team leader will tell us, especially if quality % is a big hitter
Our champion should give us that
The crew manager's report tells us some of that
The supervisors may point something out to us, but if management doesn't pay attention to our concerns, why should we listen to their concerns?

I only know from direct feedback

Do you understand what OEE means? Do you pay attention to it?
I'm not trained
The charts are not updated
No, maybe half of our charts are useful
Some people don't want to understand
No
I know what the letters stand for, but not what it means
Nobody took the time to explain the graphs
It's the time the equipment is available, right?
I only look at the quality stuff
No one looks at anything but Morale
The charts are for the salaried people
I went to classes once, but a lot of the measurements have been added and not explained
Not much is useful to our team

Do you understand what FTT means? Do you pay attention to it?
Yes, but why isn't it on one of our charts?
Yes, because I work on Polish
Yes, I deal with repairs so I understand that
Yes. Quality gets more attention from the team

Problem Resolution

Are there recurring problems in your process that aren't being fixed? If so, what is the main reason why?
Just questionable items. Safety items get fixed
25-30% gets done
The high priority problems get fixed, depending on money
It takes forever to get things changed or fixed, especially if it can't be justified with money
There are not enough resources
Yes, one we've been trying to get fixed for a while
If it costs volume, they pay attention to it
Medical data is tracked, but people don't always go to medical. So it's tough to have data
Yes, management must be convinced if money must be spent
I'm not sure what to do if issues don't get resolved
No champion or supervisor comes to our team meeting
If it's easy and cheap, it gets done
We don't get a good reason when an issue doesn't get addressed. It causes cynicism
It depends on who you talk to about it
The only thing that matters is if trucks aren't getting off the line
Even when we proposed a solution and tested it, it was tough to get the other department to do it
We've had safety concerns for a while, with several near misses. They play the lottery with safety
If it's really costly or there's lots of red tape, things are tough to get done
If you push it enough, it may get done

Do you have the means to communicate problems to other areas that must help to resolve them? In real-time? Through CIWG's?

We may send someone to another team's meeting
We rarely meet with other teams
We detect problems from the paint sprayers. If they could see what happens, they would stop doing it quick. But rotating would be hard because of different skills
Supervisor and team leader feed back information on the radio
Team leaders sometimes spend time in another area
There's not much communication team to team
Supervisors usually handle the direct communication during the day
All 3 crews must buy off on any changes, so the team leaders must email the other team leaders
We can't work overtime to go to the other crews' meetings
We can invite other departments to our meeting
We don't go to meetings in other departments, but we can go to other meetings in this department
No, so some problems take years to get fixed
We can't be taken off the line during production, so it's tough to go to other departments
Those are the majority of the issues we deal with

Improvement Suggestions

Do you have a means to formally communicate suggestions for improving the process (not just fixing problems)?

We mostly report issues and problems and suggest a solution if we have one
It's pretty good. You can't get everything you want
Improvements are more difficult to justify than problem fixes
I guess we could, but we don't have too many
Yes, especially safety improvements

Do you make use of it? Is it taken seriously?

Yes
It's tough if no problem exists
3 out of 25 people will suggest stupid ideas
Yes, it's good with safety issues
Yes, but management doesn't always listen
Management mostly does give a reason for why they're not doing stuff
Safety improvements get done pretty quickly

Ever made a suggestion and had it implemented?

Yes, good decking made our job easier and safer
Some of them got done
No, they do what they want to do anyway.
Management feels intimidated when teams get involved, so why bother?
We made lots of changes with the cutters

Anything else you can think of relating to identifying and resolving problems?

Feedback from supervisors is good, but inconsistent
We need more specifics about our problems
This is just the same as EI
Fact-based problems get solved
We need a big board to put the previous shift's problems so we'd know what to look for at the beginning of the shift
Involvement is good if it's used, but when you don't see any change why tell anyone?
Data and charts don't matter much without accountability
Supervisors could do better with feedback
Feedback to groups is not as effective as to individuals, not that groups don't care, just that it's tough to know if you caused the problem or what you could do differently
We need measurements for the quality of repaired trucks, and if a second defect was in the same area
We need to know how many tutones went through the line
½ hr meetings are not enough, but the full hour wasn't always used either
Is management actually going to do stuff?
People like to be told good things as well as bad things
Communication here is not good, even with email and charts
How should we communicate with other departments? They don't seem to care about our problems
I would like to see an air filter change schedule on the charts
For those that care about things, ½ hr meeting is not long enough
We need quicker feedback from Polish
It would help if warranty data was broken down into where it was sprayed – clearcoat, basecoat, or prime
We need to know the exact location of defects
Give reports each hour
Why should I communicate if no one is listening?
We need feedback from Trim about specific problems
I would like to see a count of the number of stops for problems at Hang, etc.
Can we measure and chart the downdraft?
Management should be sure to communicate important things to the teams
Make information available. You can never have too much information
If no one explains what all the charts mean, why is someone putting in the work to make them?
We need more input from salaried champions in the meetings
We need to be able to tell individually who has a problem
Give feedback on what happened before, last night. Don't just worry about the present
Track problems and the solutions, so you can see what is being done in real time.
If feedback is both good and bad, it can get the competitive spirit going, like fantasy football
How about a light at each station if you are having problems, not just when the line is stopped?
There is too much data
Acronyms are confusing – OEE, SQDCM, etc.
Graphs are too complicated. No one is going to spend much time trying to decipher them
It would be good to have meters showing the paint properties, viscosity, etc.
Opinions are sometimes dismissed. At least respect them
People will always find the easiest way to do a job
FTPM is done because it is cheaper
With external quality concerns, we need to feed it back to exactly where it happened
Feedback gets distorted by being passed through too many people
When certain issues aren't getting resolved, why?
I want to get general information about what's going on

We need direct feedback related to our job
Is there anything we can do to make someone else's job easier?
Every other month, management tells us where problems are on different crews
Clean the ovens
General SQDCM information is not really helpful at our meeting
We're mostly concerned with job safety
Communicate problems to the right source, or issues won't get addressed
Sometime we have to go higher up to get a problem fixed
Issue escalation is easier to do now that upper management supports it

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