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Implementation of Lean Manufacturing during the Process Definition phase of a new engine program

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Abstract

The Toyota Production System (TPS) is recognized by many to be the paragon for manufacturing system design. As such, it has been imitated by several companies inside their production plants in an effort to reap the manufacturing performance of Toyota. While imitation typically consists of "retrofitting" existing traditional plants with TPS, this thesis focuses on the actions required to design a greenfield plant to be a TPS plant.

This thesis focuses on a specific phase of the Product Development cycle of a new engine program. This phase occurs between the initial engine prototype builds and the release of product and process drawings to the machine tool vendor in order to begin tool build. During this six-month period several activities need to occur in order to assure a lean product and processes are developed. This thesis first describes the design driver that guides the design of each of these activities, and then describes each activity in detail. These activities are viewed from the perspective of a Simultaneous Engineering (SE) team responsible for designing the engine's cylinder head. While some of the issues are specific to a cylinder head, many are shared by all engine SE teams. In this context, each issue will be explained, the trade-offs will be noted, a description of the team's decisions will be expressed, and the final decisions will be evaluated.

The last sections of the thesis describe the ex. post. results of the cylinder head team, and focus on the entire engine team's culture. Culture is presented as a topic that is often ignored by companies attempting to mimic TPS. Ignoring the culture of TPS is to ignore the foundation of TPS and will result in failure. This thesis describes the culture of the engine team and explains how this culture affects the design of a lean engine plant. Successes and struggles with this engine team's culture are good lessons for other teams attempting to design lean plants.

There are two main goals of this thesis. The first is to provide an analysis of a product development process and identify recommendations for improvement. The second goal, similar to the first, is to provide a step-by-step guide for the design of future lean engine programs.

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1 Introduction

A great deal of literature has been written about lean manufacturing and the Toyota Production System (TPS) from which lean manufacturing is modeled. The word lean, coined by Womack et. al. in the Machine that Changed the World, has grown to be synonymous with the most efficient way to manufacture products. Numerous articles and books describe the foundation of the Toyota Production System and the elements and tools required to run lean production. Yet while this literature describes how to utilize TPS within a full volume production environment, not much has been written which discusses how to design this environment. This thesis will attempt to describe the major lean tasks that need to be performed during the product development stage of a new program in order to ensure that the plant is designed to be a lean plant. Specifically, this thesis will look at a new greenfield engine plant that a major automotive manufacturer, Cobana (name disguised), is building that will be designed and run as a Cobana Production System plant (CPS plant). CPS is Cobana's version of TPS. It will look at key tasks needed to be addressed between production prototype build and the release of "OK to tool" drawings to machine tool vendors in order to ensure that this plant will be a CPS plant.

This thesis defines the time between prototype build and the release of "OK to tool drawings" as the "Process Definition phase". It will focus on the issues that need to be addressed at both a plant and an individual machining line level during this phase. While the machining line that is illustrated is the Cylinder Head line, these lessons can be applied to the design of all machining lines. In addition to the discussion of tangible issues, this thesis will also look into the cultural issues associated with lean design lean. Typically the cultural piece of TPS is overlooked when trying to mimic the successes of TPS, and oftentimes it is the most important. Throughout the thesis certain "asides" will be mixed in, describing actual events that occurred during the process definition stage and discussing culture as it relates to a given section. A border around these sections delineates them from the rest of the thesis.

This chapter will explain the concept of a "CPS plant" and describe the time period called the Process Definition phase. The second chapter will take this concept and explore different ways to guide its design during this phase. Given this guide, the third and fourth chapters look at the specific tasks that must be accomplished by manufacturing management and the Simultaneous Engineering (SE) teams respectively. The fifth chapter gives a timeline for these tasks. The sixth chapter focuses on the culture of the SE team and how this culture can either aid or hinder design of a CPS plant. The final chapter summarizes the thesis and indicates area for future research.

As a road map for this chapter, it will first briefly describe the Toyota Production System and describe the type of operating environment that CPS is trying to emulate. This environment serves as the vision for how all manufacturing plants should be run.

Yet in order to run these plants as "CPS plants" they must be designed lean. Section two will describe the product development process that leads to plant design. The third section will illustrate the fact that Cobana's product development process lacks proper guidance in how to designed a CPS plant. The fourth section will describe the piece of the product development cycle and the specific product that this thesis focuses on. The last two sections provide a framework for looking at and evaluating decisions during the product development cycle.

1.1 The Toyota Production System

The noted Japanese manager, Shigeo Shingo, describes the "basic principle of the Toyota production system" as the "total elimination of waste"[1]. Indeed, all elements of the Toyota Production System (TPS) can be traced back to this basic principle. Shown below are the seven wastes of TPS and the "House" of TPS. The five components of the house are documented in a popular "House of TPS" format[2], with a brief discussion of each component. For a more in-depth look at these components, and of TPS in general, please refer to the references of Monden, Ohno, and Shingo.

<u>Seven wastes</u>

1. Overproduction
2. Delay (Waiting)
3. Transport
4. Processing
5. Inventory
6. Wasted Motions
7. Defective Parts

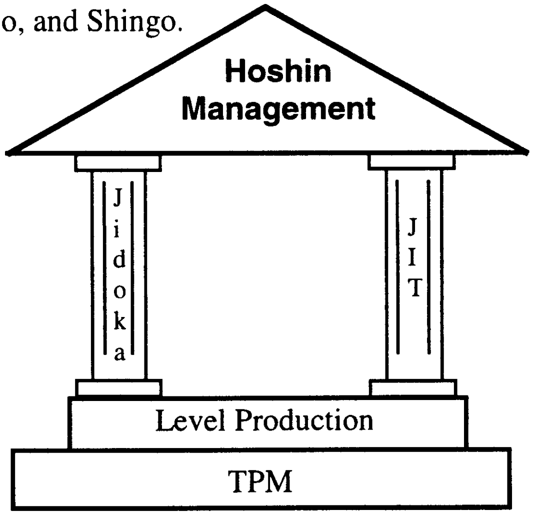

Figure 1-1 House of TPS

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[1] Shigeo Shingo, *A study of the Toyota Production System*, Portland, OR. Productivity Press, 1989, p. xxvii

[2] Interview with Toyota, Georgetown manager, Sept 27, 1997

The first component is the pillar of Just-in-Time (JIT). JIT refers to the practice of "producing the necessary product in the necessary quantities at the necessary time"[3]. It is commonly know as the "pull system" and relates back to the basic principle by eliminating waste of overproduction, inventory, and even defects.

The second pillar, Jidoka, or Autonomation, is the separation of operators from machine, and the use of in-station process control to eliminate the possibility for sending a defective part to a downstream station. This pillar eliminates the waste of waiting and of defects.

The third component, forming the floor, is level production. This means balancing production to coincide exactly with demand. An ideal for this is to produce with a batch size of one, where each customer order will be met with a single piece of production that meets the demand. Level production eliminates waste in overproduction, lot delay (batch processing delaying delivery to downstream processes), processing delay, inventory and also defects.

The fourth component, forming the foundation, is Total Productive Maintenance (TPM). TPM is a culture at Toyota where all of the workers understand that in order to keep

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[3] Yasuhiro Monden, Toyota Production System, Norcross, GA: IE and Management Press, 1993, p.5

production running, the equipment must be maintained in top condition. In a sense, it is the foundation for all other production activities. All operators are responsible for maintenance, and maintenance schedules are religiously completed and monitored. Documentation and feedback are diligently performed and given to machine tool suppliers for improvement. TPM transcends the seven wastes, as no production would be possible without it.

The final component, forming the roof, is Hoshin Management[4], which is a management tool for aligning all of the people in the organization to the company goals. Often looked at as annual planning process, it attempts to align people's daily jobs and tasks with the overarching goals of the company. As the roof of TPS, it serves as a blanket for all of the systems below it.

The Toyota Production System can also be thought of in terms of an overarching Philosophy. The understanding of this philosophy can help guide imitators of TPS, such as the Cobana Production System.

Overarching TPS Philosophy[5]

- TPS is a system: One must optimize the system and not its parts
- TPS is practical and pragmatic: There are no absolutes, no set rules
- TPS is robust: It is designed to handle uncertainty and complexity
- TPS requires balanced objectives, yet the priority is Safety, Quality, Delivery, Cost

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[4] A good reference for Hoshin Management is Shiba, Graham, and Walden, *A New American TQM*, Chapter 14

The importance of this overarching philosophy is that it shows that imitators must understand the *system* of TPS in its *entirety* and not attempt to piecemeal implement TPS parts. However this philosophy is also somewhat discouraging. The fact that TPS is practical and pragmatic means that it is impossible to systematically copy. Thus there is no set roadmap that one can follow to "copy TPS". Cobana understands this fact and their Cobana Production System incorporates the elements of TPS into their business goals, while keeping the general philosophies the same. Thus a CPS plant describes *an ideal plant where the system of CPS is utilized with the goal of total elimination of waste.* Since the underlying vision is similar for TPS and CPS, and since lean manufacturing describes the elements of the two, the terms TPS, CPS and lean will be used interchangeably throughout this thesis.

While the ideal state will never be reached, the performance difference between a well designed and run lean plant and a traditional plant can be outstanding.

Metric	**Toyota Kamigo No.9**	**Chrysler Trenton**	**Ford Dearborn**
Plant size (sq. ft)	310,000	2,200,000	2,200,000
Hourly employment	180	2250	1360
Line rate (per day)	1500	3200	1960
Labor-hours/ engine	.96	5.6	5.6
Inventory (average)	4-5 hours	2.5-5 days	9.3 days

Table 1-1 Comparison of lean and traditional engine plants[6]

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[5] Adapted from H Kent Bowen "The Toyota Production System", Harvard Business School

Although the data is somewhat dated, and Toyota's line rate is less than either Ford's or Chrysler's, Toyota is clearly running a more efficient plant. The labor hours per engine is 1/5 that of the other two, and both employment and inventory are an order of magnitude less.

In summary, CPS defines an ideal state production system whose goal is the elimination of waste, and a CPS plant is a plant that achieves this state. Once this goal is defined, a new program platform can use it to guide their design during the product development process. The next section explains Cobana's product development process.

1.2 Cobana's Product Development Process

This section describes the high level guidelines of Cobana's product development process, outlined in the Cobana Assurance Planning Manual (CAP Manual, or CAPM). The manual outlines Cobana's "strategy used throughout the Product Development Process to consistently develop and produce a product which will satisfy the customer." This strategy is the integration of six overlapping processes in the product development (PD) process, which are referred to as "Simultaneous Engineering" (SE). Simultaneous engineering, also called Concurrent Engineering, refers to the grouping of different function members (product, process, quality, etc) into cross-functional teams (SE teams) that perform their work "simultaneously". Shown below is the product development

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[6] Adapted from McElory, "Quality Goes In Before the Part Comes out," Automotive Industries, November 1984, p.52

process complete with milestones.

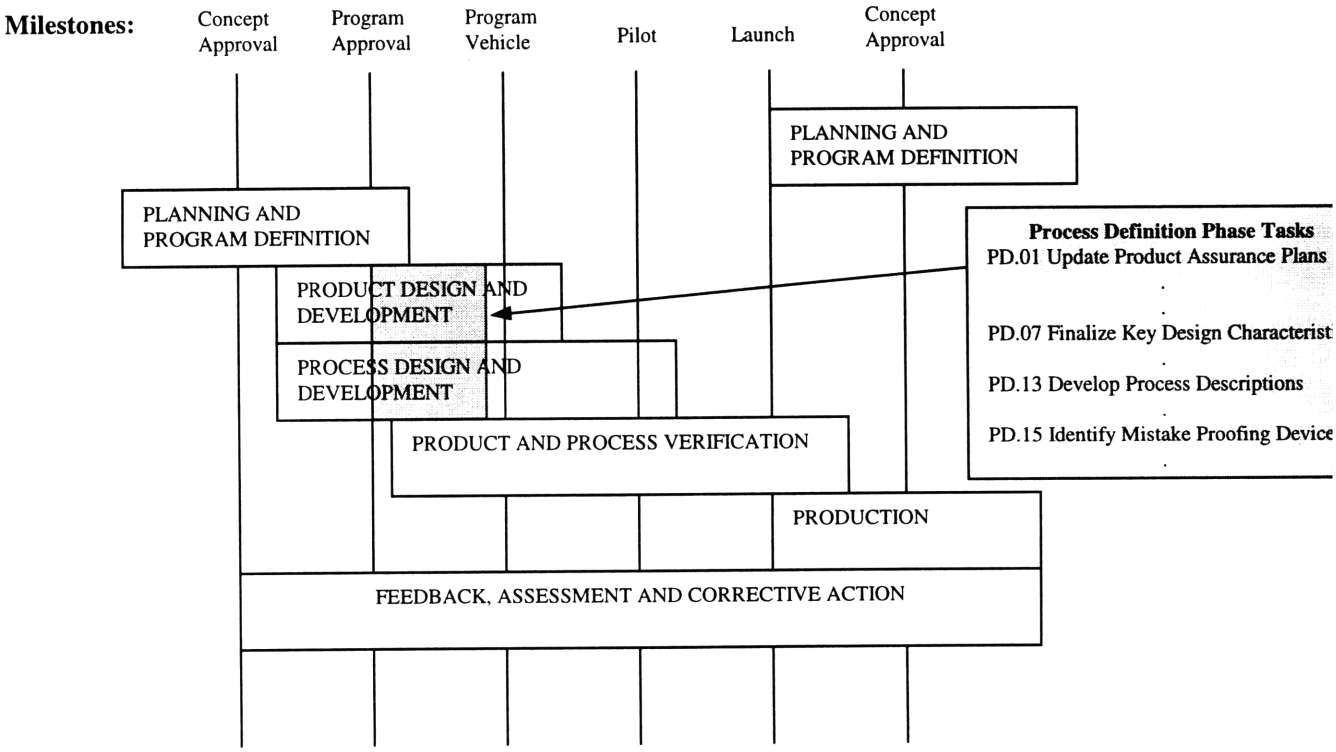

Figure 1-1. **Cobana Product Development Process**

There are several points of interest on this time line. For one, it represents a traditional product development cycle (Wheelwright, Clark, 1992) with comparable phases, but there is no indication of time on the chart. This is because one goal of the CAP Manual is to continually reduce the cycle time of PD process. Another interesting note is that the start of Product Design and Development coincides with the start of the Process Design and Development . In reality, a typical US auto company the start of process design lags product design by three months[7], as did Cobana's new engine program.

In addition to the chart of SE activities, the CAP Manual describes the high level tasks that need to occur between each milestone. For each of these tasks the CAPM assigns responsibility, defines deliverables and provides measurements to assess success. Examples of a few of these tasks are illustrated in the grey box above.

1.2.1 The missing element in the Product Development Process

As mentioned above, this manual only defines high level tasks that need to be performed during the PD process. While these tasks do contribute to robust processes and exhibit themes of the CPS, they do not provide a structured design guide for developing a CPS product or a CPS plant to produce this product.

What is missing is a structured guide for each phase of the PD process, which would provide design direction to the members of SE teams. This guide would describe in detail all of the issues and tasks that need to be addressed and present recommendations for design . What the CAP manual lacks, this thesis hopes to provide, for a specific period of the PD process, referred herein as the Process Definition Phase.

1.3 The Process Definition phase

The grey segment of the product development process figure illustrates a specific

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[7] Kim Clark, Takahiro Fujimoto, *Product Development Performance*, Harvard Business School Press, 1991, p.217

time period of the PD process. This six month period stretches from the time when initial prototypes are built to when the production processes (machining and assembly) are completed and given to the machine tool vendors to begin construction of the machine tools. This is a critical time during the PD process as the machine tool designs are finalized and subsequent changes cost a lot of money. The graph below shows the significance of this period.

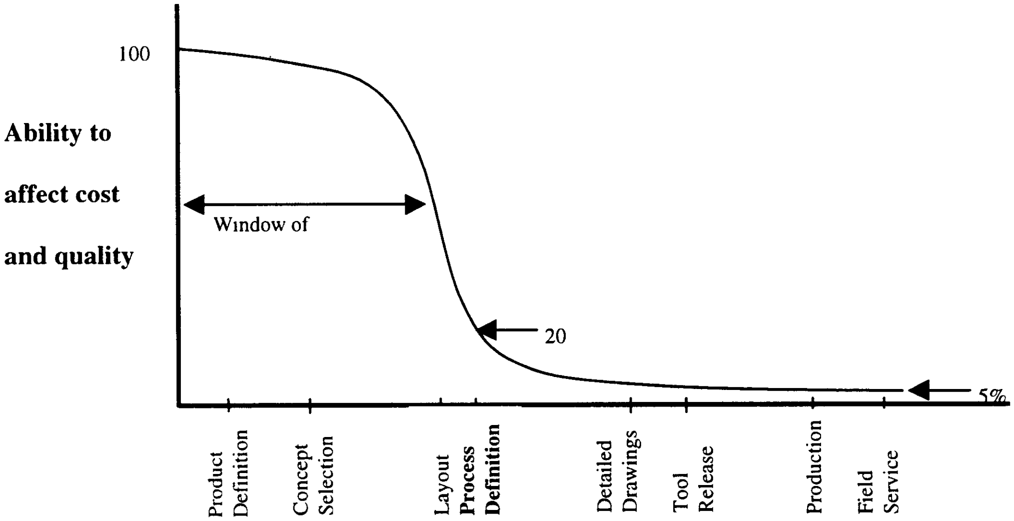

Figure 1-1 How cost and quality are defined through Product Development[8]

The "window of opportunity" represents the time from the beginning of the program to the end of the Process Definition phase. During this time, changes to the product and processes have minor effects on the final quality and cost of the product. The end of the Process Definition phase corresponds to the steep slope of the cost function. After this point, 80% of the variable cost and the quality of the product are defined and subsequent changes to the product or processes are very expensive.

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[8] Modified from Bowen, et. al, The Perpetual Enterprise Machine, p.205

During the Process Definition phase, request for vendor quotes are issued, quotes are received and machine tool vendors are selected. Once selected, the vendors become part of the SE team and share the task of improving the initial product and process. Because a large part of this time period consists of continual modification of the machining or assembly processes, this thesis refers to this period as the "Process Definition phase". The goal of this phase is to define a robust process that will reliably produce parts with high quality and will contribute to the running of a CPS plant. Within this Process Definition phase, this thesis will focus on a specific engine program and within that engine program on a specific machining process.

1.4 The plant, product and thesis focus

Most engines are comprised of 5 major machined parts, the crankshaft, the camshaft, the cylinder block, the connecting rods, and the cylinder head. Most engine plants have dedicated machining lines, which machine each of these parts[9]. In addition to the machining lines, engine plants typically have two assembly lines, which perform the cylinder head sub-assembly and full engine assembly. The sub-assembly consists of preparing the machined head for engine assembly by attaching valves, rocker bars, rocker arms, etc., and installing the camshaft.

This thesis will focus on the cylinder head machining line. It will look at the key issues that need to be addressed by the cylinder head SE team during the process

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[9] Some plants do elect to outsource one or more of these parts

definition phase. It will also discuss plant-wide issues that need to be addressed by plant management that affect all lines, examples of which are: material handling, general plant layout, and tool change strategies. The goals of this thesis are to:

1. Describe this engine program's process definition phase and the decisions made during this phase.
2. Critique these decisions through a framework.
3. Provide a manual for future programs that are attempting to design CPS products and plants.

The intent is to develop this manual to partially fill the missing piece of the Product Development process and encourage others to fill the rest. The platform team understands that their final design will not be perfect. In order to assess the extent of improvement possibilities, it is important to be able to measure the success of the design. This thesis will attempt to do this through the Safety, Quality, Delivery, Cost, and Morale metrics.

1.5 Evaluating design based on SQDCM

The Safety, Quality, Delivery, Cost, and Morale metrics are what are used by Cobana to assess the level of CPS attainment for plants and processes. Similarly this thesis will use these metrics to evaluate the decisions made during the process definition phase and recommend improvements to future programs. SQDCM is a fairly simple framework, which discusses the impact on safety, quality, delivery, cost, and morale that results from each decision. For example the decision to hold an extra days worth of inventory may increase our ability to better Deliver to our customer, however it will come at an added

Cost of inventory and may decrease Quality by making it harder to detect defective product. A weakness of SQDCM is that it does not weigh any category more important than another, nor does it assign specific rating levels in each of the categories. However, it is useful to get a high level understanding of the ramifications of decision that can allow you to assess tradeoffs to some extent. For example, in the case above we might decide that implementation of a Just-in-Time inventory pull system may result in an equally good Delivery as would result from an increase in inventory, while providing better Cost and Quality. In such a case the JIT system is more effective and should be implemented. This example also illustrates a typical failure of SQDCM. Many programs focus on just one of these metrics, such as the "lowest Cost engine" or on the Delivery that the excess inventory provided above. In order for a system to be effective, there must be a *balance* between Safety, Quality, Delivery, Cost and Morale. In contrast to the excess inventory, the JIT system above also provides a much better balance in SQDCM.

1.6 Summary and notation

This chapter gave an overview of the Cobana Production System and the Cobana product development process. It showed the gap that exists between the two and how there is no good roadmap to guide a platform team attempting to develop a new product. The term platform team will be used extensively throughout this thesis, and refers to all members of the engine program: product engineering, management, finance, quality, process engineering, etc. Another term that is extensively used is Advanced Manufacturing Engineering (AME). AME members are the process engineers, who are responsible for design of the manufacturing process and the installation of the machine tools. The thesis focuses on AME in Chapter 4 when it discusses specific cylinder head line design issues.

In addition to identifying the product development guide gap, this chapter also discussed SQDCM as a process for evaluating new design guides. The next chapter will focus on how to begin guiding this design.

2 How a 5-person vision translates to operational requirements of a CPS plant

Given our design task, the next question is how do we design our plant to be a CPS plant? Related critical questions are: What are the tools and information required to run a lean plant? How do we translate these requirements into a design? How do we know we have covered everything? These questions are the foundation behind the design of a CPS plant. The stronger this foundation is understood by the entire organization, the better the plant will be designed and eventually run.

No design guide will be perfect, but this chapter will discuss a few design guide alternatives that can be employed to design a lean plant: axiomatic design, direct copy, or use of a vision. Problems exist with each of these design methods, which will be discussed in each of the sections. Ideally, these alternatives should provide a set of operational requirements, such as "there will be 2 items of Work-In-Process between each machining station", that the plant will be designed around. Ultimately, as indicated by this chapter title, it turned out that the use of a simple vision became the design guide that led the design of Cobana's new engine and of its manufacturing plant.

2.1 Axiomatic design

Axiomatic design can be a tool to specify design of a lean plant. It is the process behind which specific customer requirements (CRs) are mapped into functional requirements (FRs) that a design must meet. For example, a customer requirement for a golf club might be, "gets the ball over a sand trap". This might be then mapped to the functional requirement that, "the club fact must provide the loft to allow the average golfer to get a golf ball over at 10ft high object from 15ft." These FRs are then translated into specific design parameters (DPs), which are physical elements that meet the functional requirements. In the example above, the corresponding DP would be a "56 degree angled club face". A diagram of these interactions is shown below.

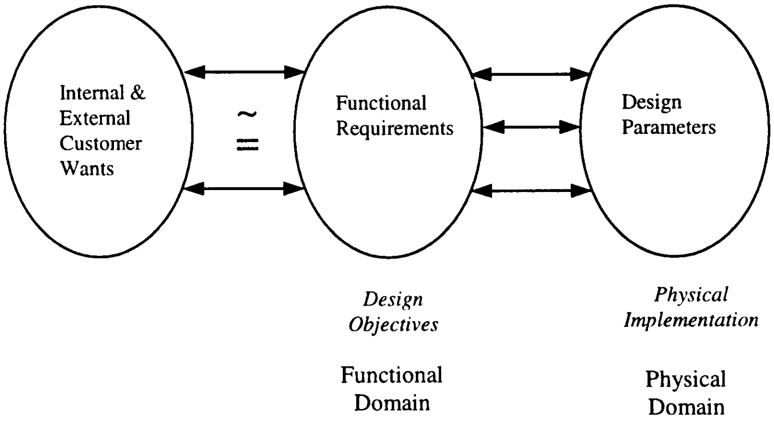

Figure 2-1 Axiomatic Design Mapping

In designing a CPS plant the functional requirements are the elements of the CPS such as elimination of waste, TPM, JIT, Autonomation, etc., and the design parameters are the physical design of the plant and the plant systems, such as distance between machines, operator responsibilities, standard work procedures, gauging process. Axiomatic design arrives at the lowest level DPs, such as "distance between machines is less than 1 meter", by using high level FRs and DPs to cascade down to the lower level specific design parameters. An example of this cascading is show below:

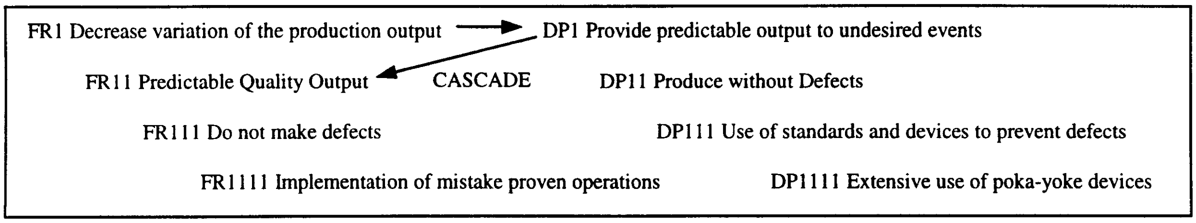

Figure 2-2 Example of Axiomatic Design Cascading[10]

This example ties into one piece of the TPS Philosophy discussed in section 1.1 above. The point that "TPS is robust: It is designed to handle uncertainty and complexity" is encapsulated in FR1: Decrease variation of the production output. To satisfy this functional requirement a method for providing predictable output to undesired events is a physical, albeit high-level, solution. This high level DP can then be cascaded to a lower level FR. In this example, in order to have a method for providing predictable output to undesired events one must functionally have predictable quality output. This requirement in turn leads to another DP.

The advantage of using Axiomatic design is that if it is *used properly* it will produce a robust design that incorporates all of the customer requirements. In the case of the engine program it will provide a CPS plant. Unfortunately, Axiomatic design is very difficult to use properly. The reason it is so difficult is because it is so complete. Design of a lean plant requires the design of a tremendous number of systems, many of which are not

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[10] From David Cochran and Paulo Lima, Lean Production System Design Decomposition, MIT Production System Design Lab

independent of other systems. It is impossible to focus on the design of one system without considering its ramifications on another. These problems lead to the drawbacks of Axiomatic design, which are that it is very time consuming, very difficult to use, and very hard to teach. Furthermore, no one has been successful at modeling the design of an entire plant. A high level attempt was performed by this author and another student, which is presented in Appendix A. The attempt required many days worth of work and still does not provide a guide which would be useful to teams attempting lean plant design.

However these complications do not invalidate Axiomatic Design; as noted by Ulrich "While there are currently no deterministic approaches to choosing an optimal product architecture [in this case design of a plant], the process can be guided" (1995). Work by Cochran and Lima are attempting to provide this guide, and this area appears ripe for further research, however, in its current state, it does not provide the appropriate design guide to Cobana. Another possible guide for design is to simply copy an existing design.

2.2 Direct copy

Toyota's Georgetown, Kentucky plant would be a good candidate for copying. Motivation for copying Toyota is strong because Toyota is recognized as the world leader in manufacturing. Copying a paragon is a simple and effective way to reach the status of the paragon, however in order to do so, the model must be fully understood and capable of being copied in its entirety. As stated in Taiichi Ohno's[11] book, "To [realize TPS's] tremendous success, one has to grasp the philosophy behind it without being sidetracked by particular aspects of the system"[12]. Simply copying certain aspects will lead to failure if TPS is not fully understood.

Unfortunately, Cobana does not fully understand TPS and is thus not capable of implementing the system in entirety. Additionally, simply copying a model does not allow for improvements to it, which is one of the goals of the program director. What Cobana needs to do is copy certain Toyota systems, such as lean gauging, and andon board use, but adapt these systems to their unique design. To accommodate this uniqueness, Cobana is going to use the alternative of vision to guide one's design.

2.3 The platform team's vision

The platform team's vision is running the machining lines with about one-fourth the number of workers that an existing Cobana engine plants contains and the assembly line with one-half. This vision is a powerful guide for design because in order to be able to run efficiently with this few number of workers, every element of design needs to be made more efficient. Stating that "5 people will run this cylinder head line" creates a vision that guides development of the information systems and tools required. Additionally it serves to mitigate design disagreements when one alternative is not feasible because it will prevent 5 people from running the line. People outside of the

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[11] Taiichi Ohno is recognized as the creator of the Toyota Production System

platform team are often confused by this vision because running with "5 people" is exactly what Toyota does, and thus the vision can be construed as "copying Toyota". The difference is that the platform team is using Toyota as a benchmark for good design and not an actual mold. Later references to "copying Toyota" simply refer to taking benchmarked systems and adapting them to Cobana's unique design.

2.3.1 Translation of the vision to operational requirements

This section demonstrates how the vision of 5 people running a line translates to operational requirements. As mentioned above, in order to run the line with 5 people, the workers need to be able to keep machines running as often as possible. One tool for doing this is an information system that immediately tells workers when the line goes down and which machine caused it. Toyota uses an Andon board to communicate this information, which is an effective method of indicating when a machine has a fault, needs a tool change, or requires a quality check. The response to this information drives even more design. To prevent faults, a robust process and product needs to be designed. To minimize downtime due to tool changes, tool lives need to be maximized and tool changes need to be able to be performed quickly. To efficiently perform quality checks, a strategy that minimizes the typical waste associated with periodic and 100% visual checking is required. Similarly, the vision of running with only 5 people can drive the design of the multitude of other operational requirements for a lean plant.

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[12] Taiichi Ohno, *Toyota Production System*, pg. xvii, Oregon: Productivity Press, 1988

The biggest problem with using a vision to determine operational requirements is that this method is not structured and as such can result in the team missing many requirements. A more robust method of design would be to develop an operating plan based on past experiences, and continually improve it over the course of several programs. This operating plan would specify the ideal design of each plant system and the tasks required to develop this system. Unfortunately there are no past experience from which to work with. The platform team is currently working with consultants to develop these operational requirements for the remainder of the program and to document the lessons learned from the Process Definition phase.

2.4 Chapter Summary

This chapter examined three possible design guides for developing the operational requirements of a CPS plant. Axiomatic design offered a systematic framework for doing so, but proved to be too complex for our purpose. Direct copying of Toyota's Georgetown plant was attractive but unfeasible. The platform team utilized a vision of 5 people running a large machining line as the design guide, but recognized that a better guide would be an operating plan that has been developed and improved over several programs.

Given the use of the vision, the actual lean design of the engine and the plant can be broken into two sections. The first deals with plant wide issues, such as material handling and tool changing strategies. These issues must be addressed by management and communicated to all of the SE teams either before, or early in the process definition phase, as the SE teams processes depend largely on the design of these plant wide systems. The second piece of the design relates to each SE team specifically. These issues focus on the individual machining or assembly lines and the machining or assembly processes that are used. While many design guidelines can be shared between separate machining lines, the specifics of developing the robust processes will be unique. The next two chapters focus on the plant-wide issues and cylinder head specific issues. Both describe the issues at hand, discuss the tradeoffs, explain the team's decisions, and evaluate these decisions.

3 Key Plant-Wide Management Lean elements

This chapter will focus on the macro-level elements that affect all areas of the plant. These need to be addressed early on in, if not before the Process Definition phase, as these effect the processes of each machining and assembly line. The management of the platform team is primarily responsible for the design of these systems, with secondary input from each of the SE teams. Each section of this chapter focuses on a specific element. Some sections briefly explain the issue at hand and specify recommendations. More complex elements are covered with in-depth sections. These sections begin with describing the issues involved, then, where appropriate, they discuss the different options and how the vision of five people running the line support or hinder different options. After discussing the options, each section will explain the decision made by the platform team and then evaluate the decision, where appropriate, based on the SQDCM framework and recommend improvements for future programs.

3.1 Machine tool specifications

One of the major contributors to a lean plant is a machine tool design that supports the lean environment. These machine tools need to have a variety of elements that support quick problem detection and correction, total productive maintenance, and robust product and process design. If these elements are not specified in the machine tool specifications they must be both designed and paid for after the submission of the purchase order. Even worse, if they are not caught, they will not be included at all.

3.1.1 Cobana's Machine Tool Specifications

Historically, Cobana has only specified machine tool specifications in terms of how the machines need to be able to function in Cobana's plant environment and a list of capability requirements for the machine to be "bought off on". Very little has ever been included that specify the CPS elements that need to be designed, and when CPS is discussed it is typically in abstract terms which allows personal interpretation and does not force compliance with the machine tool vendor. For example, "A high degree of reliability and maintainability must be assured to keep the Mean Time to Repair within 5 min", and "Design should consider easy maintenance access to all components and for tool change" is the extent that robust, capable and in-control processes are addressed. Neither of these specifications explain specifically what Cobana would like from the design and as such does not hold the machine tool vendor accountable for these CPS elements.

3.1.2 Toyota's Machine Tool specifications

While Cobana's specifications are typically 20-30 pages[13], Toyota's are often thicker than 80 millimeters[14]. The difference is that Toyota specifies every element that must be included in the machine tool design in order to support their lean production system. A few examples are shown below, with several more in Appendix B.

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[13] This does not include references to supporting documents that specify non-CPS company standards for the equipment

a) Limited number of acceptable standard tool holders

Toyota specifies exactly 2 tool holders for taps and 3-4 tool holders for drills. This eliminates waste in spare parts but also allows faster and more reliable tool changes, as the operators only have a few holders to track and less chance of using the wrong tool holder to set tools.

b) Different spindles in the same station must use different holders, and must only be able to accommodate one specific holder.

While the previous specification lessened the chance of using the wrong tool holder, this specification takes the previous one a step further: it eliminates that chance for installing the wrong tools in a spindle by using Poka-yoke (error proofing).

c) Specific ladder logic programming for fixed component switches (FC switches).

This specification encompasses two elements of lean production. For one it mentions the requirement to uses FC switches that use air-pressure through a fixture to verify that the part is correctly clamped. This greatly reduces the chance of a crash due to incorrect clamping. Secondly, it shows that not only the hardware for the machine tool controllers has to be common, but all of the logic involved with the controllers does as well. This common logic specification minimizes the time for error correction, as an electronics engineer only needs to understand and debug one logic design.

d) Diagram of how a control panels legs must be designed to allow sweeping underneath.

This specification shows the detail that Toyota goes into in their Machine Tool Specifications. If the design of a control panels legs must be specified, it is easy to understand why their machine tool specifications are so thick.

3.1.3 The reason Toyota's specifications are more thorough than Cobana's

The main point of this section is not to criticize Cobana's specifications for not being as thorough as Toyota's. Rather, it is to show the potential for improvement. When

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[14] Information from trip to Georgetown, Nov 17, 1997

comparing any manufacturing environment to Toyota, one must realize that TPS has been running for over 40 years and it is a system based on Kaizen (continuous improvement). It would be unfair to compare a 3-year-old system to a 40-year-old system, especially a 40-year-old system that continually improves. Therefore, the challenge in improving Machine Tool Specifications is to implement a system that allows continuous improvement. Toyota is excellent at knowledge transfer: when an error or failure occurs it is well documented and feedback is given directly to the Machine Tool Vendor; then a new machine tool specification is written for future programs.

3.1.4 Improvement suggestions and SQDCM

Similar to Toyota, Cobana needs to develop an effective method for implementing this knowledge transfer. Currently, Cobana uses "legacy" specifications, meaning they are only periodically updated by a special, non-product development group. No system exists to encourage feedback from new programs. Machine tool specifications need to become a living document, which is required to be updated through the course of every product development process. Such a system is critical because, as the examples above demonstrate, good machine tool specifications improve every element of SQDCM.

3.2 Machine tool supplier selection

It is imperative that a machining line's machine tool supplier is or becomes knowledgeable about the concepts of CPS. A supplier must understand the vision and the goals of the SE team in order to be an effective contributor to the Simultaneous Engineering phase of process design. Without them, the supplier's recommendations are based on what worked in the past, not what will work in a CPS plant. As a consequence, many of their suggested designs will have to be greatly modified.

The engine program's machine tool companies were selected based on a competitive bid. The criteria for selection were based on technical expertise, extent of foreign presence, supplier quality, cost and also level of CPS understanding.

However, despite this evaluation it is still clear that some suppliers really do not understand CPS. For example, one of the suppliers recommended using eight meter buffers between every station because that is what one of their customers used before. Eight meters corresponds to 16 pieces of work-in-process between stations, which is far more than Toyota's average of three. This example shows how simple reliance on the machine tool supplier's recommendations will not result in a CPS line.

3.2.1 Improvement suggestions

In order to get the machine tool suppliers knowledgeable about the concepts of CPS, additional training must be done as soon as they are selected to be suppliers. The most effective way of doing this would be to develop a CPS course that would focus on the elements of CPS as they relate to machine tool design. Such a course would review the sections of Cobana's improved machine tool specifications and explain the reasons for each of the sections. It would describe the history and give a systems level overview of CPS, so suppliers will understand that this is not just "another program of the month", rather a system focused on consistency and fit. In this manner, suppliers will understand the design drivers behind such things as the level of WIP between stations, and they will be much more effective SE partners.

3.3 Tooling partner selection

A tooling partner is a tooling supplier who is brought on during the design phases of a new program. These partners can be valuable aids during the SE process. Their expertise in tooling can provide recommendations to process and product changes that will make a machining line more robust. For this reason the platform team selected three major tooling partners; each partner providing assistance in their area of expertise. However, an agency problem arises with tooling partners, as they are more inclined to recommend their own tooling even though it may not be the best for a given situation. It will be important for an experienced Cobana tool engineer to review all tooling layouts and proposed tool procurement to ensure that this agency problem does not compromise quality.

3.4 Tooling management strategy

While different metal cutting tools are utilized for different machining processes, their lifecycles are similar. Most tools are sharpened, set-up in a tool holder to a specific length, installed in a machine, and then removed to be re-sharpened after their use. After several of these cycles the insert or bit will be thrown away. The method for processing the tools through their cycles is a part of a tooling management strategy and can be performed in either a centralized or decentralized manner.

3.4.1 Centralized vs. Decentralized tooling

Decentralized and Centralized tooling represent the two extremes of the spectrum of how to set up your tooling storage, repair, and preparation. A completely decentralized tooling design has all tooling functions located in each machining line. In this environment all tool storage, tool sharpening and tool setup is done in an area located on each machining line. In a centralized design all of these functions are performed in one area of the plant which services each machining line.

3.4.1.1 Benefits of Centralized tooling

Centralized tooling contains the following benefits:

- Experience associated with dedicated workers performing tool sharpening and set up
- Minimal fixed cost investment in sharpening and tool height setting
- Minimal space associated with one location for all tool management

By having dedicated workers performing all tool management, you develop expertise in these workers, which results in more accurate sharpening and set-up. This accuracy is especially critical with tools that are difficult to sharpen and set-up such as milling heads and broaches. Furthermore, the cost associated with having sharpening stations and equipment to set-up such tools is expensive, and centralized tooling permits only one set of such equipment. Finally this equipment takes up a large amount of space in the plants and centralized tooling allows a minimal amount of space.

3.4.1.2 Benefits of Decentralized tooling

Decentralized tooling contains the following benefits:

- Minimal number of tools in the system
- Just-in-time tool sharpening and set-up
- Ownership of tooling by line operators

Just-in-time tool sharpening and set-up offers many advantages over doing these tasks in bulk. For one it results in fewer tools in the system. With bulk sharpening and set-up, many more tools have to be set-up in order to keep the machines running while other large batches of tools are processed. Perishable tooling as a whole represents a significant capital investment that can be reduced by only setting tools when they are needed. Another benefit of this just-in-time management is that it results in better quick problem detection and correction. If a tool is set improperly the operator will notice a defective part immediately and will quickly realize that the cause was due to his tool setting. This rapid feedback will result in the operator improving his tool setups, which in turn will lead to better long-term quality.

Ownership represents another large advantage that decentralized tooling has over centralized, although this advantage is less tangible than just-in-time. The culture that we would like to develop in our plant is the feeling that these lines are owned by the operators. This culture can lead to a much higher Morale than a traditional culture. It is the operators who need to feel responsible for the number and quality of the parts *they* produce. At Toyota operators are ashamed when they send defective product to their downstream customer. Their culture results in improved quality because the operators feel like they are the ones responsible for quality. In order to install this culture of ownership, operators need to be given as much control as possible over their lines, and tool set-up represents a great deal of control.

Does ownership lead to higher morale?

Not necessarily, say some publications. These publications focus on the problems that many automotive plants have had at attempting to introduce "self directed" work teams. Mike Parker and Jane Slaughter published an interesting labor book, which systematically trashes the concept of teamwork among UAW workers. They summarize lean manufacturing as a way of stressing the manufacturing environment in order to expose weaknesses in the environment. This stress is similarly believed to be transferred to the workers who must operate in this environment. They note, "overall the system itself multiplies personal stress by continually increasing the demands on the individual while reducing personal control" (Parker, Slaughter, 1988)

Despite the clear biases of this book, other more impartial sources have also questioned the increased morale that ownership brings. Janice Klein notes that the "attack on waste", which is the essence of TPS, "inevitably means more and more structures on a worker's time and action" (Klein, 1989). Workers who were used to the freedom associated with the wastes of traditional manufacturing, including common "breaks" that occurred due to the waste of waiting, do indeed often struggle with a lean environment. However, initially designing the plant to be lean, and introducing workers to this design from the beginning, should eliminate this desire for a traditional environment. As noted by Klein "if for example, worker participation programs are implemented after JIT...workers will not be invited to imagine greater freedom just when the new processes takes freedom away".

Designing and participating in a lean plant will give workers the freedom to design their environments to best suit their work. They will feel the responsibility associated with meeting production, and be given the tools to affect production. This responsibility should result in a higher morale than a worker who "punches in" in the morning, performs a single job all day, and then "punches out" in the afternoon. As noted by one worker on the Toyota Georgetown line: "I run this line. I wouldn't want it any other way."[15]

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[15] Comment from team member on a trip to Georgetown, Nov 17, 1997

3.4.1.3 Engine program's tooling strategy

The engine programs tooling strategy represents a trade-off between the extremes of Centralized vs. Decentralized. In this system, modeled after Toyota's tooling strategy, drills, reamers, and taps will be set-up in decentralized areas of each line, while most of the other tooling will be set-up in a centralized area. Because ownership is highly valued in our environment we would like to have all tooling set-up on the lines (increase Morale), however, setting up tools such as milling heads and broaches require expensive equipment and this requirement makes decentralized set-ups for these tools prohibitively expensive (decrease Cost). Certain special tools will be set-up in the machines themselves. These tools require high-precision set-ups that can not be ensured by either a centralized or decentralized set-up (increase Quality). Simple transportation and reinsertion into the machines will result in unrepeatable settings for these tools. All tool sharpening will be done in a centralized area due to the expertise and equipment required (increase Quality). Reliable sharpening requires expensive equipment and experienced workers to run the equipment.

3.4.1.4 Engine program's tool management procedure

Similar to the tooling strategy, the engine program's tool management procedure is modeled after Toyota's. The figure below is a diagram of the procedure[16].

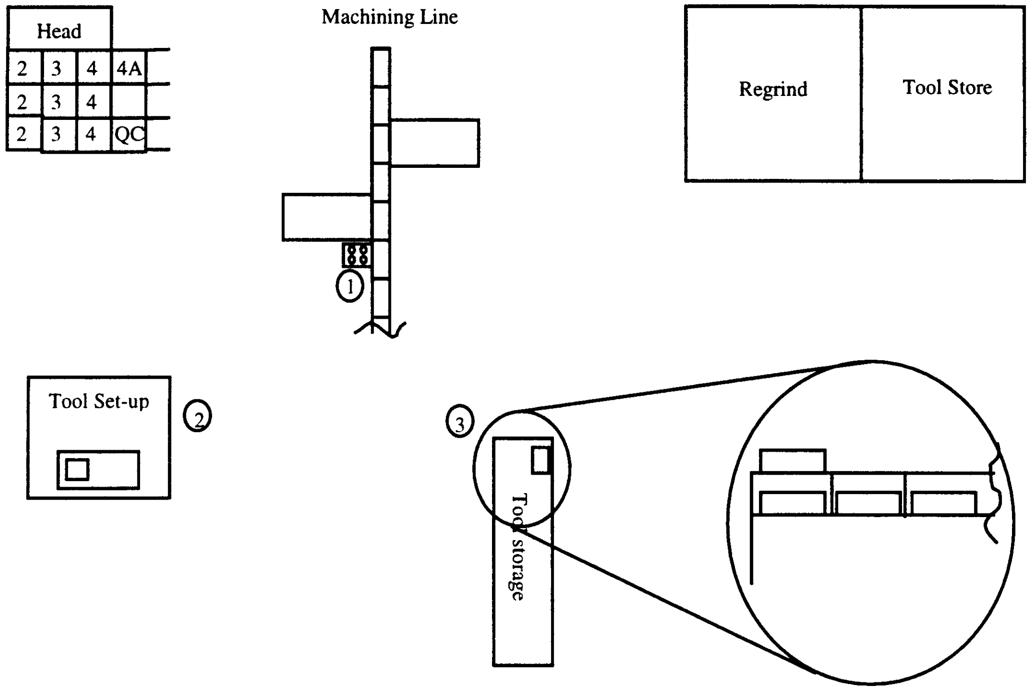

Figure 3-1 Tool Management procedure

The diagram shows the layout of a typical section of a machining line and the location of the regrind department and tool storage. Tool change procedure begins with the andon board, which flashes a yellow light on the station that needs to be changed. An explanation of the andon board will be covered in Chapter 4. The operator, noticing the flashing light will go to the appropriate machine and begin the tool change by utilizing the "4 button tool stop" (position 1 in the figure). The first button stops the machine after the next cycle. The second button retracts the tooling and allows the operator to open the machine to change the tools. The side of the machine also has a shelf on top of which is a box with two red slots and two blue slots. Blue slots are to hold sharpened and set-up tooling, while red slots hold dull, used tooling. The operator replaces the used tooling with the sharpened tooling, and places the used tooling in the red slots. The operator then presses the third button on the panel that returns the tool to the ready position and cuts one part. This part is checked by the operator, and if it is good, the fourth button is pressed which starts the line back on full automatic. The operator then takes the box to the tool set-up crib (position 2 in figure) to remove the tool holder from the dull tool. The tool set-up crib is centrally located on a machining line and consists of benches and shelves to hold tool holders and equipment need to set up drills, reams and taps. The holders are left at the tool set-up crib and the dull tools are carried to the tool storage shelves located on the aisle of the machining line (position 3 in the figure). A blow-up of a section of the tool storage shelf is shown in the figure. The top shelf is used for boxes with dull tools, the lower shelves hold sharpened tools that are ready to be set-up in tool holders. The operator places their box on the top shelf and then grabs the appropriate box with sharpened tools. This box is then carried back to the tool set-up crib and the tools are set to the appropriate height. The equipment required to set up drills, reamers, and taps is a bar with a one-axis motor and a simple needle position gauge. Each box has a bar code on the side that when scanned will adjust the gauge to the appropriate tool-set height for the specific tool. After setting the tools, the operator returns the box to the machine that required the tool change.

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[16] Information from trip to Georgetown, Nov 17, 1997

Two times per shift the used tools are replaced by the regrind personnel. These people belong to the material handling department and are responsible for replacing all sharpened tooling back on each of the machining lines. Once the dull tools come back to the regrind department they are either sharpened or if they can not be sharpened are traded to the tool storage for new tools. The regrind personnel are the only people in the plant who can get new tools, and they can only do so by exchanging old tools.

3.4.2 Block change vs. In-process change

Another piece of the tooling strategy is when to change your tooling. Some plants perform a block tool change where they run the tools for a full shift and change them between shifts. This tool change takes anywhere from 15 min to 1 hour, depending on how many people are involved in the change. Under block changes, the tool lives of the tools that are changed are approximately one shift. An alternative to block tool changes are in-process changes, where the tools are run to the end of their lives and then changed while production is running. The only exception for changing tools early is when multiple tools are used in the same head. In this case, the longer-life tool is changed at the same time the shorter-life tool. In-process systems require both tool counters to signify when the tools need to be changed, and accumulators to provide buffers to prevent loss of production during tool changes.

3.4.2.1 Benefits of a block tool change

Proponents of block tool changes argue that their method results in greater production, as the line only shuts down at the end of the shift for tool changes. In addition, because of this, the inventory that is required to buffer in-line tool changes is not required. Furthermore, because the tool change is done in a controlled manner at the end of the shift the tool engineer can effectively monitor the tool wear due to the daily production and do effective tool life studies. These studies would be more difficult to do if the tool changes were sporadic.

3.4.2.2 Benefits of an In-process tool change

Proponents of in-line changes point to the fact that their method is actually more efficient than block tool changes. Providing 1-5 pieces of work-in-process per operation buffers the line against losing production and allows the line to run continuously as with the block tool changes. Furthermore, no overtime or supplemental employees are required at the end of the shift to do tool changes. Another benefit is that tool life is maximized because tools are only changed when they reach the end of their lives. With block changes one is guaranteed to replace some tools prematurely. On the same note, tools are *always* changed when they reach the end of their lives. One problem Cobana plants have run into is that employees sometimes do not block change their tools at the end of their shift[17]. This results in many quality problems for later shifts. A similar, but extremely important additional benefit of in-process tool changes is that they are flexible when you

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[17] Conversation with Scott Knaggs, supervisor of a Cobana cylinder head line, 10/7/97

change your production numbers or wish to run overtime. Block tool changes will result in under and over utilization of tools under these conditions resulting in waste of tools and waste of scrap, greatly increasing your variable costs. Finally, in-line changes allow the workers to work with the tool engineers to increase tool lives. The concept of running a tool to the end of its expected life and then checking the results is a much more scientific method of doing tool life tests than pulling tools mid or post-life. In addition, in-line tools provide an incentive for the workers to increase tool lives- it makes their jobs easier.

3.4.2.3 Engine program tool change strategy and SQDCM

The program elected to use the in-process tool change strategy. And from an SQDCM perspective this is the correct choice. From a Quality perspective, production will not continue if tools are not changed exactly when they are supposed to, in-process tool changes eliminate the "forgotten" block tool changes that can occur between shift changes and will result in defects. From a Delivery perspective in-process tool changes are fully flexible to changes in production numbers. For example if a tool needs to be changed after 1200 cycles and production is increased from 1000 parts per shift to 1300 parts per shift, the tools will not be run past their proper lives. This example also shows how in-process tool changes decrease Cost. The same tool in the initial 1000 part per shift block change production environment would either be changed at 1000 parts, which would result in a waste of 200 cycles on the tool, or it would be run to 2000 parts, which would result in quality issues. Furthermore, cost is minimized by eliminating the need for employees to work overtime to change the tools.

In summary, the engine program tool management strategy is identical the strategy of Toyota's and as such it represents a benchmark for a CPS plant. All tools will be sharpened by regrind personnel, drills, reamers and taps will be set-up by line operators, and most tools will be changed in-process (grinding wheels an other difficult tool changes will be scheduled off-shift). The next two sections describe the guidelines for material handling and layout strategies. These strategies are explained with the framework of the seven wastes.

3.5 General material handling strategy

Another plant-wide element that needs to be addressed early in the Product Development phase is the material handling strategy. A good material handling strategy is focused on the elimination of waste. Transportation waste is reduced through the design of point-of-use material handling. This guideline encourages the design of lines such that each downstream process is fed by an adjacent upstream process, minimizing the travel between them. Point-of-use is especially critical for the design of where the castings will be delivered to the lines and where the finished-machined parts will join the assembly line. A better point-of-use design results in smaller distances between these areas.

Waste of waiting is eliminated by separating operator from machine. In a traditional machining environment an operator is dedicated to loading a machining line. Since they can load parts faster that the machines cycle-time, they waste a great deal of time waiting for the machine to cycle. Instead, the material handling system and the operator's job description should be defined to allow this operator to perform other tasks in addition to the loading of the line. This design concept, know at Toyota as jidoka, separates the operator from the machine and allows them to perform multiple tasks while the machine is processing parts. Toyota accomplishes jidoka through their material handling strategy by having the loading of *all* machining lines performed by one worker and designing the level of loading automation to allow this. For example, the cylinder head line, which produces twice as many cylinder heads as the block line produces blocks (6-cylinder line), is loaded by robot, while the block line is loaded by a worker. This worker belongs to a separate material-handling group (not one of the 5 people on the machining line) whose responsibility is delivering material to the entire plant. An additional part of the material-handling strategy is designing the layout to make these workers jobs easier.

3.6 Generalized layout

A large piece of layout design involves optimizing the lines for material handling. In general, all points of delivery for material to the lines are located on or near an aisle. This allows the material-handling group to optimize their deliveries and meet their takt time with minimal waste. Other stations that are typically located on an aisle are washers and in-line quality checks such as leak testers. Washers located on an aisle provide easy access for a sump tanker in order to drain and clean them. Similarly, leak tester rejects can be easily removed from the line.

In order to run the line with 5 people the layout must also be as compact as possible. This allows all workers to be able to quickly access all machines and prevents the tendency to have sections of the line that workers consider their own. A compact line encourages workers to assist their team members when their team member's workload becomes heavy. Similarly, design stresses the elimination of areas of the line that are isolated from others in order to promote this teamwork. In addition to having a compact line, walking distance for operators is minimized within the line as well. This is a huge issue for a CPS plant. By only having 5 operators running major machining lines, these operators are going to be walking much more than their traditional plant counter parts. To be successful it is critical that there is no wasted motion by these operators, as a lean environment magnifies all wasted motion. To help reduce this waste, the tool set-up area is located as close to the tool drop-off area as possible and gauges are located right next to the point where the parts are taken off the line for checking.

Many people in AME felt that a "U-shaped" layout was ideal. "U-shaped" cells have gotten a lot of attention in recent articles and books for their ease of leveling and balancing production. To these people this benefit in some way translated into an efficient way to design a machining line layout. However the benefits from "U-shape" are based on the ability to adjust labor to level production. A transfer machining line does not adjust cycle time to meet takt time[18], thus given the other design drivers it tends not to resemble any "letter of the alphabet".

Aisles are as narrow as possible. Toyota's standard for aisle width is 0.9 meter, which corresponds to the width of a maintenance trolley that is used to change large pieces of equipment. This width is especially significant because it drives the design of your line from a maintenance accessibility standpoint. In reality, Toyota does not use forklifts or cranes to change large equipment. Rather, the maintenance staff hoists the equipment out of the machine with a chain thrown over the heavy C-10 strut they have in the ceiling. This strut is a significant expense for Toyota, however they feel that the compactness it allows merits the cost.

Culture of uncomfortable newness

The debate on the width of the aisles for the engine plant exposed some discomfort that many of the AME supervisors had with adopting lean elements into their plant. This discomfort was caused because the proposed design was so radically different from what the supervisors were used to. The width of Cobana's aisles are typically greater than 4 meters and such a width is perceived to be required for using some of the heavy equipment located in the plants. When the Toyota expert proposed reducing our proposed aisle width to 0.9 meter there was several comments such as "We can't do that" and "That won't work". The expert then explained how the 0.9 meter design was driven by the width of a maintenance trolley. This gave the supervisors a path out. There was an unspoken understanding that we would still have forklifts and cranes removing the heavy equipment in the plant and 0.9 meters was far too small for this. After some more discussion the group decided that 1.5 meters was the more acceptable. Many people remained uncomfortable by this design, but to them 1.5 was better than 0.9. People understood the need to make the aisles as narrow as possible, however experience made them uncomfortable with this new design.

Aisles serve another design purpose. Toyota tries to pool all of their extra "dead" areas from their lines on an aisle instead of leaving them isolated. This allows useful room for future expansion. Toyota designs their plants to run for 50 years and understands that over the course of this time, several programs will be manufactured in each plant.

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[18] A transfer machining line uses a transfer bar, set at the cycle time of the cutting machine to move parts from one station to the next. This cycle time typically stays constant throughout the product life of the machined part. Labor reduction causes more machine downtime, which does modify line output, but this output is not dependent on the shape of the line.

In summary a CPS plant requires an efficient material handling strategy and layout. These guidelines are less specific than the previous sections, because different products will require different layouts. However, the platform team needs to understand how the layout and material handling are related to the seven wastes and how the framework of these wastes will help design a plant that minimizes them. One of the major wastes in a production environment is the waste of inventory, and as mentioned before this waste needs to be balanced with the requirement for delivery. The next section discusses how to make this trade off with in-process buffers.

3.7 Buffer Strategy- Machining

Another critical element that affects the layout is the size and location of buffers. Toyota utilizes three types of buffers[19]:

- In-process buffers on the machining lines
- End of machining line buffers
- Off-line buffers

In-process buffers are the buffers that occur between operations of a machining line. In a traditional plant these buffers are designed based on simulations that take into account tool changes, quality checks and estimated downtime based on past mean-time-to-failures and repairs. Toyota's in-process buffer strategy is to only buffer to accommodate *downtime associated with tool changes and visual checks*; thus buffers are typically positioned after operations that have long or frequent tool changes.

Instead of complex simulations, which Cobana requires as part of the machine tool specifications, Toyota calculates buffer sizes using a fairly simple spreadsheet. This spreadsheet calculates the amount of time blocked or starved at each operation based on manually inputed buffers. These buffers can be adjusted to modify downtime as desired. As long as the sum of each machine's cycle time and its downtime is less than the takt time of the product, additional buffers are not needed. The spreadsheet requires inputs for the tool lives of all of the tools and the time required to change each of them. Consequently the specific buffer size can not be determined until all of the tools are selected, which typically occurs after the process definition stage; however, preliminary estimates are useful to identify potential process problems. This information can be used to help design a more robust machining process.

AME is challenged because they have no good studies to show the typical lives of their tools or the length of time required to change them. This is one area where they will have to rely heavily on the experience of the tooling vendor and machine tool supplier. This experience will ultimately determine the success of Cobana's buffer design.

Buffers at the end of the machining line are used by Toyota to balance the demand from assembly and the supply from the machining lines. Cobana will mimic Toyota's typical two hour buffer which accommodates the difference in line breaks between the machining and assembly and buffers against common machining line downtime.

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[19] Information from trip to Georgetown, Nov 17, 1997

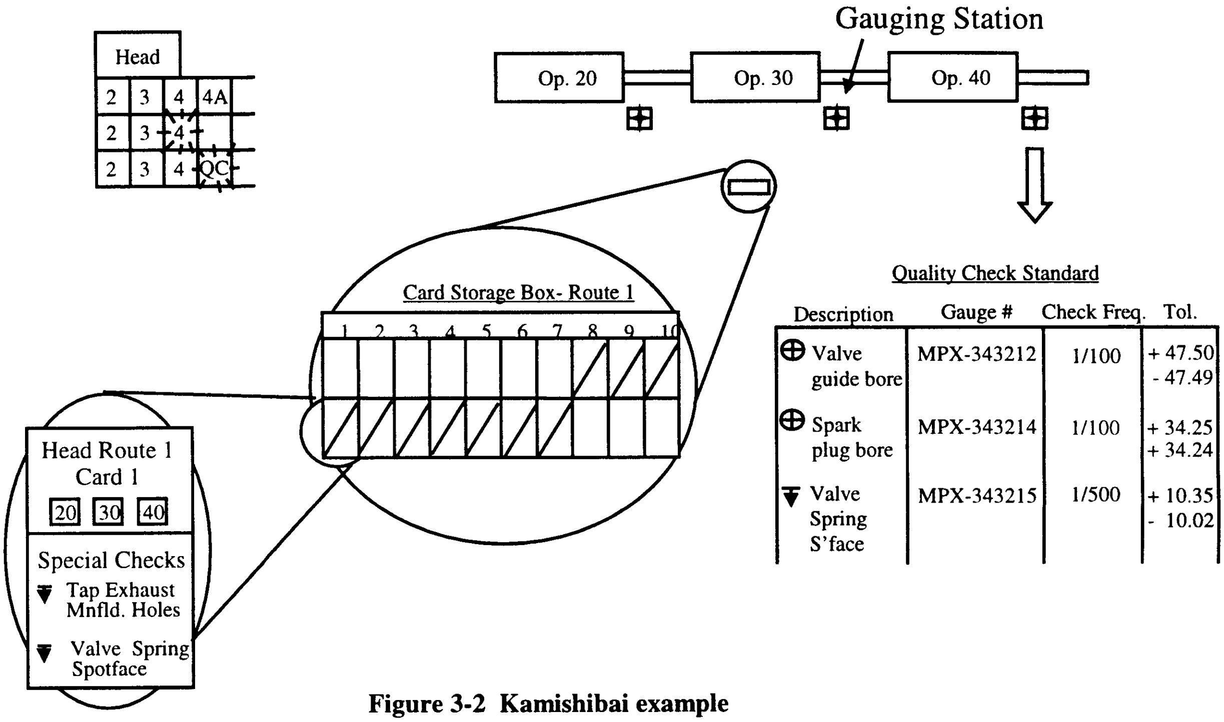
Toyota also stores a set amount of material off-line. This material is used in the case of emergencies, for example when a machine breaks down and a part must be ordered from Japan. Toyota Georgetown initially held five days worth of inventory at the end of each machining line. Currently there is only one shift. This material is cycled through production through the course of a month so that contamination is minimized. Cobana has not finalized the amount of their off-line inventory.

Buffers present the ultimate balance between Delivery, Cost and Quality. The larger one's buffer, the longer it takes to identify a quality problem and the greater the material holding cost. These negatives need to be balanced with the reality of variability and the effect that variability has on delivery. While a lean plant does have a fair amount of inventory, given their production system, their variability is much less than in a traditional plant. As such they have much less inventory and have better Delivery, Cost, and Quality than a traditional plant.

3.8 Gauging Strategy- Machining

In order for a machining line to be run with a minimal number of workers, all activities have to be relatively well balanced to assure that production does not shut down. A lean gauging strategy attempts to balance the amount of gauging that occurs throughout the course of a shift. Toyota uses the concept of kamishibai to control their in-process gauging, which is diagramed below.

The foundation from kamishibai comes from the fact that some features are critical and should be checked every hour or two, while others are not critical and only need to be done a couple of times a shift. Typically these features also take a long time to gauge. For example manufacturing hole location is critical and must be checked every hour, while a non-visual check of chatter on a valve seat is not critical and may not be needed more than once per shift. Furthermore, either complex equipment is required to check a valve seat or a very lengthy manual process. This manual process consists of application of tape to the seat and a comparison check of the contact area to an acceptable contact master. Kamishibai is a relatively simple way of balancing these types of gauge checks. Machines are grouped into routes of two to three operations and each route has a set of cards and a card storage box. A typical Quality Check Standard sheet is located at each operation which states the description of the quality check, the gauge number, the frequency of check, the nominal dimension, and the required tolerance. When the Andon board indicates that a quality check needs to be performed, the operator goes to the card storage box, and grabs the next card in line (in the diagram this would be card number 8). This card has a picture of the operations and lists the "special checks" that are not performed each time but need to be checked during this check period. By having 2 to 3 "special checks" per card Toyota is able to effectively balance the length of time it takes to perform every quality check. After the check is over the operator replaces the card; every check takes between 15-20 minutes.



Quality Check Standard

Description	Gauge #	Check Freq.	Tol.
⊕ Valve guide bore	MPX-343212	1/100	+ 47.50 - 47.49
⊕ Spark plug bore	MPX-343214	1/100	+ 34.25 + 34.24
▼ Valve Spring S'face	MPX-343215	1/500	+ 10.35 - 10.02

Figure 3-2 Kamishibai example

The reason why the development of a gauging strategy is required during the process definition stage, even though quotes for gauging equipment aren't finalized, is that each AME team needs to address how they plan to balance the gauging times. The team needs work with quality and product engineering to ascertain what tolerances are critical and determine how frequently all of the checks will be performed. Only by establishing the gauging strategy and frequency will the AME team be able to purchase the correct gauging equipment for their requirements. An improper gauging strategy or equipment will at best result in unbalanced quality checks, hindering production, and at worst will prevent the machining line from running with five people. As such, the gauging transcends Quality, affecting Delivery as well.

The cylinder head team is still in the process of developing tolerances for the head and as such is behind schedule in developing a gauging strategy with the determination of what features to check periodically.

3.9 Tolerancing

In order to run a machining line with 5 people, operators need to be able to gauge a part quickly and accurately. At Toyota this requirement drives much of the specifications for tolerancing from the product perspective. Both design and manufacturing engineering informally review tolerances of non-critical features. They attempt to design these tolerances to be able to be checked with simple go/no-go gauges. Design engineering will regularly open up non-functional tolerances to accommodate the design of a simple gauging process. This is critical from a Cost and Delivery standpoint, as the gauging equipment will be much cheaper and the gauging process much quicker.

Cobana has attempted to do this in a more formal way with SE teams, whose job is to work out such issues. Unfortunately for much of the Process Definition phase a cylinder head part print was not available from which to negotiate tolerances. Certain tolerances were reviewed on other parts, however.

Tap depth definition: design for simple gauging
One example where tolerancing can be opened up on Cobana's prints is in tap depth definition. Tolerances on tap depth are +/- .05 mm. Such a tight tolerance is excessive for non-critical tapped holes. By opening this up to +/- .2 mm Cobana can use the simple hook gauge that Toyota uses[20]. This gauge is a piece of metal wire with a slight hook at the end. The wire is inserted into the tapped hole and hooked on the lowest thread. A green "go" line and a red "no-go" line on the wire are painted to indicate if the depth is too shallow or too deep. This gauge is much cheaper and quicker than the traditional screw gauge.

3.10 Inspection

As mentioned before, in order to have a minimal number of workers on a machining line there must be virtually no waste of operator time. Because the time required to visually inspect a part is much less than the cycle time of the line, the job of a 100% inspector is as wasteful as the job of the loader / unloader mentioned before. As a result, the job of an inspector is only a part-time job in a lean plant, and this worker is part of the 5 person machining team.

Toyota uses an operator to perform 100 percent inspection. She will receive notice for a visual check from the Andon board, walk to the end of the line, and visually check about 40 parts that are waiting for her. Downstream processes are considered customers of the upstream process. The part closest to the machining line's customer (unchecked part) is physically stopped from proceeding by some object (typically a dowel) that is placed in a drilled hole in the part. Once the 40 parts are checked, the object is placed back in the next unchecked part.

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[20] Information from trip to Georgetown, Nov 17, 1997

While the actual process for accumulating the parts for a visual check has not been discussed, it is understood that an operator in the engine plant will do the inspecting on a part-time basis.

3.11 Summary

This chapter focused on ten key issues that need to be addressed either before or early in the Process Definition phase by the program management. In many of the cases above the vision of five people running the machining lines served as a guide to dictate design. In others, Toyota's benchmarking confirmed their design was superior and accommodated Cobana's five-person vision. Each section explained the necessity of each element and showed how adoption of the designs resulted in a better or more balanced SQDCM.

The next chapter focuses on the micro-level elements of a specific machining line. Similar to Chapter Three, Chapter Four will discuss the key elements that need to be addressed by the specific AME team during the Process Definition phase to ensure their line can be run with five people and in a way that improves and balances SQDCM.

4 Key SE team lean elements

This chapter will focus on the key micro-level elements that need to be addressed during the six-month Process Definition phase by each SE team. Each team is responsible for an individual machining or assembly line. The line that this thesis focuses on is the Cylinder head machining line, although the elements are similar for every machining line. Each SE team needs to focus their energy on designing a robust machining process, as the initial proposed processes are seldom robust. The definition of robust means to minimize output variation given variations in inputs and environment. A good process design will be robust and will ensure maximum machine uptime and minimum scrap, effectively improving Delivery, Quality and Cost. Furthermore, issues of increasing operator ownership arise, which can also improve Morale.

The first section focuses on the selection of datum from which to reference all of the cutting operations. This is critical because it defines the tolerance stack-up for many features and, as such, the quality of the part. The second section discusses the use of Process Failure Modes and Effects Analysis (PFMEA) as a tool for making the machining process more robust. The third section explains the machining andon and explains how it is used to communicate information to the operators. The fourth section focuses on the automation style and how a first-in-first-out design can improve SQDCM.
The last section explains the operator's responsibilities in a CPS plant.

4.1 Datum selection- Joint Face vs. Exhaust face

Shown below is a diagram of a cylinder head[21]. The joint face mates with the cylinder block and forms the top of the combustion chamber, the cover face mates with the cylinder head cover, and the exhaust face and intake face mate with the exhaust and intake manifolds respectively. In order to machine any part, primary, secondary and sometimes even tertiary datum location schemes must be defined. These locators are typically faces of the part or specific manufacturing holes from which all the machining processing is referenced. Cobana typically uses the Joint Face as the primary datum and manufacturing holes on the Joint Face as the secondary and tertiary datum. Their machine tool vendor, however, typically uses manufacturing holes on the exhaust face as primary datum. The selection of primary datum has been a greatly debated issue. The sections below discuss the benefits of both schemes and explain on which scheme the Cylinder Head team has decided.

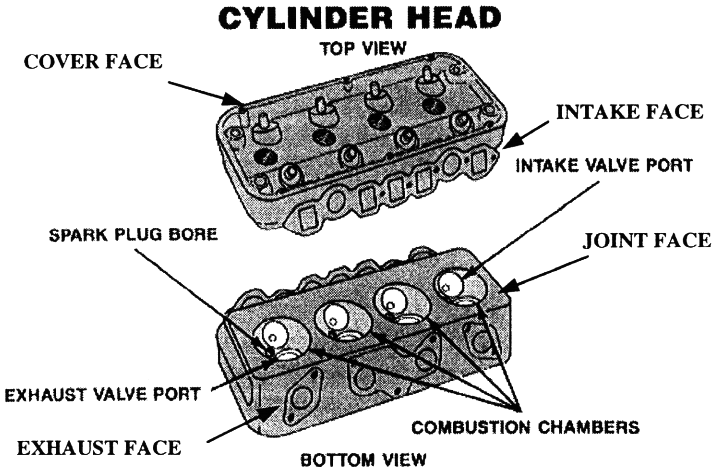

Figure 4-1 Cylinder Head schematic

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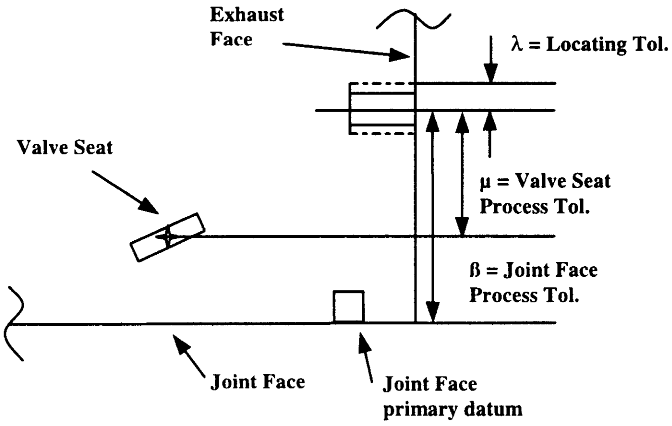
[21] Adapted from web picture: Web picture, www-personal.washtenaw.cc.mi.us/~eileen/Cylinder_head.html

4.1.1 Benefits of using the joint face as the primary datum

The benefits of using the joint face come primarily from a functional tolerance perspective. By using the joint face, tolerance stack-up is minimized and the part has the potential to be held to a closer tolerance. This is true because from a functional perspective all of the critical features need to be referenced from the joint face. Below shows a diagram of the two locating schemes. It is important to note that since the joint face is such a critical feature it is machined in two different passes. One forms the semi-finished face and the other forms the finished.



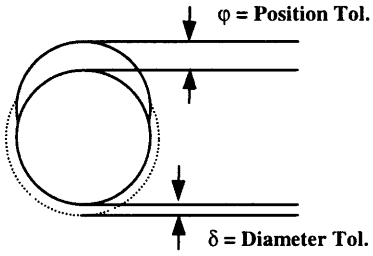


Figure 4-2

Tolerance Stack-up between Valve Seat and Joint Face

Figure 4-3

Location Tolerance breakdown

The figures above depict the tolerances between the location of the joint face and the location of the valve seat. This distance is one key characteristic of the cylinder head and it effectively illustrates the difference between the two datum schemes. Figure 4-2 depicts the tolerance stack up in the vertical direction using the exhaust face as the primary datum. The locating tolerance in this figure encompasses the error involved in machining the manufacturing hole in the exhaust face. Figure 4-3 breaks down this locating tolerance into the error in the machined location of the hole (positional tolerance) and the error in the diameter of the hole. Figure 4-2 also shows the location of the joint face primary datum. Notice how there is no locating tolerance stack-up given this datum.

The exhaust face datum scheme has the following tolerances:

1. ß the Joint Face processing tolerance. This is the processing tolerance associated with cutting the finished and semi-finished joint face. This tolerance is common to the exhaust face scheme and the joint face scheme.
2. μ is the Valve Seat processing tolerance. This is the processing tolerance associated with cutting and inserting the valve seats. This tolerance is common to the exhaust face scheme and the joint face scheme.
3. λ is the location tolerance. This tolerance is unique to the exhaust face scheme. As shown in the figure on the right it can comprise the diameter error and actual positional error. *Depending on how you reference certain dimensions, the location tolerance can be either just the diameter tolerance or both the diameter and position.* In the example above both the valve seat and joint face are machined using the exhaust face manufacturing hole as the primary datum. In this case both items are machined by locating on the same manufacturing hole, thus no positional tolerances apply. Since the locator can still be off by the diameter tolerance, this tolerance still

applies. If the valve seat used a different reference datum for machining, both tolerances would apply.

As described above using the joint face as the primary datum provides a smaller tolerance by λ. If the addition of λ to the tolerance stack-up results in a non-functional design then the joint face should be used as the primary datum.

4.1.2 Benefits of using the exhaust face as the primary datum

The benefits of using the exhaust face come from a machine tool design perspective. By using the exhaust face, the machines are much simpler, cheaper, and more reliable. This is true because the clamping and locating scheme is much simpler when the exhaust face is used to locate the part. When using the exhaust face to locate, the part is set on fixed dowels which locate on the inside of the manufacturing holes. The part is then clamped from above using a simple fixture that moves straight down. In this case gravity assists the clamping process. By using the joint face, the clamping and locating fixtures are much more complicated. Clamping now has to occur in the left / right plane which is where the tooling must reside. To accommodate this, retractable dowels must be used instead of a fixed pin locator. These dowels will slide out of the way when the part is unclamped and transferred to the next station. This added motion will lead to wear and a less accurate clamping over the course of the machine's life. Another problem with having the machining on the same plane as the clamping is that longer tools are required in order to clear the clamping. This added length will lead to greater tool deflection and less accuracy in machining.

4.1.3 Cylinder Head datum decision

Comparing the two datum opportunities there seems to be debate about which method will result in a better machined part, regardless of the tolerance scheme. The Cylinder head team has decided to use a combination of the two locating schemes for their process, but has modified the original Joint Face proposal to use the finished joint face to locate instead of the semi-finished joint face. For all of the roughing operations (operations that occur before valve guide and seat insertion) and for final joint face and cover face milling, the exhaust face will be used to locate. For the remaining finishing operations the final joint face will be used. This location strategy gives the benefits of both datum schemes. Since a majority of the critical features are located with respect to the finished joint face, this face is used for the finishing operations, while simpler more reliable fixturing can be used on the roughing operations. The benefit of using the exhaust face location scheme during the final joint face machining is that this allows the joint and cover faces to be machined at the same time in one fixture, which minimizes the tolerance stack-up between them.

Tolerance Stack-up: critical SE cultural issue
One area that is difficult to fully comprehend is the tolerance stack-up. It is very easy to get confused when trying to figure out the differences between both datum schemes. It is critical, however, for all SE team members to understand the correct tolerance stack-up. This is because from an engineering and processing stand-point the selection of the wrong scheme can lead to a part that can not be manufactured within functional tolerance. Conversely, forcing the use of the joint face datum scheme for all processing can result in unnecessary Cost in machinery and possibly even in Quality issues due to added difficulties in machinery.

From a cultural perspective it is vital that engineering and manufacturing work together to agree on the ramifications of different data schemes. Lots of time can be wasted fighting among "camps" and this fighting can lead to non-robust processes as well.

Once the datum scheme is selected the machining process can be modified to be more robust. The PFMEA is one tool that can aid in this modification. The next section will describe the PFMEA in detail: how to prepare for one, how to run one, and examples from the results of the SE teams PFMEA. These examples are broken into three sub-sections:

1 Tool-life effects (Cost)
2 Machine uptime effects (Delivery)
3 Scrap and repair effects (Quality)

4.2 Process Failure Modes and Effects Analysis (PFMEA)

An important requirement for running a machining line with only five people is that the process is robust. Unfortunately, qualifying the robustness of a process is an extremely difficult task. Typically this is a subjective determinate from plant management, made once the line is running at full volume. Obviously this feedback is ineffective and unavailable during the process definition stage. One method of assessing the robustness of a line and actually utilizing feedback is to use a Process Failure Modes and Effect Analysis. The PFMEA is a tool for identifying potential future failure conditions that can compromise the quality of the part, as well as estimating the probability of these conditions occurring. Although Toyota does not use PFMEAs for their processes, PFMEAs can be useful tools for making a process more robust. Furthermore, aside from subjective expert advice, this is the only tool that exists for developing a CPS machining process.

4.2.1 Quick PFMEA overview

The process for a PFMEA consists of the PFMEA team reviewing every station of the entire process and brainstorming possible causes of failure. Once the possible causes are identified, the team must then assign a severity of each failure on a 1-10 or 1-5 scale. For every failure the team will brainstorm one or more root causes of the failure which will be assigned a frequency of occurrence, again on a 1-10 or 1-5 scale. After identifying the causes of the failure the team must then decide what detection mechanisms *currently* exist in the process and the odds of these mechanisms detecting the failure. These odds also map to a 1-10 or 1-5 scale. The Risk Priority Number (RPN) is calculated by multiplying the values for Severity, Occurrence, and Detection together. Depending on the scale the team must decide what minimum level of RPN merits attention, and what can be ignored. Attention is given by assigning action items to individuals to reduce the occurrence or improve the detection. Once these items are in place the team can determine a new RPN.

4.2.2 PFMEA preparation

In order to have an effective PFMEA a team needs to be assembled with the appropriate expertise. Essential members consist of AME, machine tool companies, and people who are familiar with similar machining processes such as a supervisor of cylinder head line. These people represent the bare skeleton of expertise and experience to be able to effectively identify possible failure modes, as well as the severity, occurrence and detection of them. If available, tooling suppliers should also attend. They provide key expertise in material cutting, and can explain the impact of difficult machining processes. Additional members that are useful are controls specialists, product engineers, and quality representatives. While these people are not active participants, they will be called on to contribute their expertise over the course of the PFMEA.

Scheduling of the PFMEA

Scheduling the PFMEA is a big issue. People tend to give participating in the PFMEA process less value than their typical day-to-day meetings and activities. For this reason the value of the PFMEA needs to be stressed and continually repeated and the PFMEA needs to be scheduled well in advance. There is disagreement as to the proper meeting format. Some teams decided to complete the PFMEA in a straight 3-day workshop, others broke that time into one-day meetings. It is important to note that the PFMEA is a continuously living document that needs to be worked on through the course of new product launch. As a result, a one-time 3-day workshop is not sufficient to complete a PFMEA; in addition, working on PFMEAs is a tedious process and the longer a team works in one sitting the more likely they are to miss critical failure modes. Overall, the benefits of several one-day workshops need to be balanced with the feasibility of assembling the team on a regular basis.

Key preparation that is needed for a PFMEA is the development of a scale to be used to assess Severity, Detection, and Occurrence. The model scale specified in the QS9000 manual is very difficult to utilize in practice. This is because many of the descriptions are subjective and the difference between one level and the next is often difficult to assess. For example, the criteria for a failure mode with a detection of 8 states a "Remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode". It is very difficult and very subjective to be able to distinguish this detection versus a detection of 9 which states a "Very remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode". What is the difference between very remote and remote? Additionally, a great deal of time is generally spent debating whether a failure mode is one number or the next higher one. Considering how long a PFMEA takes to properly conduct, these debates are not value added. For the reasons mentioned above a more objective ranking scale of 1 to 5 was developed for our PFMEA. This scale is shown below. Severity was broken into three sections:

1) The level of repair required for the part
2) The effect of the failure on downstream processes and equipment
3) The amount of downtime required.

The team was explained that often failures affect all three of these sections and a different severity number will be chosen depending on which section is considered. In such a case the highest number should be used. Occurrence and Detection columns were also designed to be much more objective than the QS guidelines.

Ranking	**Severity**	**Occurrence**	**Detection**
1	No repair to part required No effect to downstream process Machine downtime < 30 min	The possibility of failure is very remote. Frequency of failure: > 1 year	Controls will almost certainly (automatically) detect the failure.
2	Minor repair to part required Small effect to downstream process. Machine downtime < 2 hrs	Failure is possible but not likely. Frequency of failure: > 1 month < 1 year	Controls have a good chance of detecting the failure.
3	Major repair to part required May damage downstream tooling Machine downtime < 1 shift	Failure is possible. Frequency of failure: > 1 week < 1 month	Controls may detect the failure-50/50 chance of detection.
4	Irrepairable part May damage downstream machine Machine downtime < 1 week	Failure is likely. Frequency of failure: > 1 shift < 1 week	Controls will probably not detect the failure.
5	May result in a field failure May cause Safety issue in plant Machine downtime > 1 week	Failure is certain. Frequency of failure: < 1 shift	Controls will not detect the failure. Non-detection of failure is certain.

Table 4-1 PFMEA Scale

Another issue to consider in preparation is in what format will you record the PFMEA. Some teams used flipcharts and white boards for brainstorming and recording. The cylinder head used software on a laptop that was projected onto a screen. This allowed the team to see the progress of the PFMEA and eliminated the need for rewriting it[22].

4.2.3 Cylinder Head PFMEA results

The goal of a PFMEA, as mentioned before, is to identify potential failure modes that could occur in production. A majority of these failure modes are associated with damage to a part and thus would be considered scrap and rework related issues. However the team

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[22] This software comes from the Cobana Quality Institute and is available to Cobana employees free of charge.

needs to be aware that it is equally, if not more important, to use the PFMEA to identify failures that will result in shortened tool-life or machine uptime. If these failure modes aren't identified then the team will be stuck with a process or machine that causes excessive downtime and requires more than 5 people to run. For example, Toyota, who does not use PFMEAs, found that during production one of their processes caused burrs on the front and rear faces. As a result, their milling tools for these surfaces had a tool life of less than 20 percent of what was expected[23].

Many of these tool-life and machine uptime failure modes require meetings outside of the PFMEA in order to resolve, and many relate to issues already identified through benchmarking and preliminary process reviews. The PFMEA not only serves to discover failure modes, it also provides a ranking as to how critical these issues are. This ranking represent an additional data point that can be used for assessing tradeoffs in these meetings.

The following mini-cases demonstrate an example of an identified failure mode in each of the categories of tool-life, machine uptime, and scrap and rework.

4.2.3.1 Tool-life effects

It is important to understand that tool-life failure modes can occur because of many more reasons than just an improper tool. Processes that demand too much of a tool or

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[23] Discussion with Toyota Consultant, November 11, 1997

machine tools that are not properly designed for a process can equally cause a tool-life failure mode. For example, removing 2 mm worth of material with a tool designed to remove 0.5 mm may reduce the tool-life to a fraction of its design life. In order to identify these failure modes it is critical that a person with floor experience in a similar machining environment participate on the PFMEA team. Additionally, a tooling vendor should also be included.

Generating head for Valve-seat machining- one example of a tool-life failure
Valve seat machining is one of the most difficult processes for a cylinder head. The valve seat is what the intake and exhaust valves rest against, forming the seal of the combustion chamber. Because of the high temperature environment of the chamber, these seats must be made out of special steel and inserted into a pocket in the aluminum head. In order for the valves to seal properly, the seats require three angles to be machined. The middle angle of 45 degrees is what the valve seals to and must be held to extremely tight tolerances. The other two angles are clearance angles and do not have to be held as tightly.

Originally, the AME cylinder head team and their machine tool supplier had planned on using a plunging tool to machine the seats. This tool has three cutting inserts which machine all three angles with one plunge into the seat. Figure 4-4 below shows a schematic of a plunging head. Our tooling partner expressed concern with the use of a plunging tool due to their experience with the rapid wear associated with these tools. This wear is caused by the fact that the inserts must be orientated such that their entire edges are used to cut the three angles. Any uneven wear (flack wear) along the surface of the cutting edge will result in an incorrect angle being machined.

Once this failure mode was explained to the team, they realized that this flack wear caused a significant failure mode. Not only was the occurrence high, as the tooling vendor had indicated, but the team did not have a good system of detecting it. As a response to the very high RPN the tooling vendor recommended use of a generating head. Figure 4-3 below shows a schematic of a generating head.

A one-axis generating head, like the name indicates generates the angles in the valve seat through the use of a tool located on a special slide, set at the critical 45 degree angle to the head. Except for the slide tool, the two other inserts are identical to the plunge tool. The generating head begins machining the two clearance angles with the two inserts in the same manner as the plunge head. Once these two angles are machined, the generating tool slides towards the head and machines the 45 degree angle with just the tip of the cutting insert. The use of just the tip of the generating insert is critical because tool wear will not change the angle of the sealing surface and will not result in head failures due to leaking.

The use of a generating head does raise some issues, however. A generating head is on the order of a hundred thousand dollars more than a simple plunging head, and this cost has to be justified to management. When weighed against the benefit of a significant increase in tool-life and quality, this one time expense should be considered worth its results. In addition, the added complexity of a generating head could cause additional failure modes which need to be addressed in the PFMEA process.

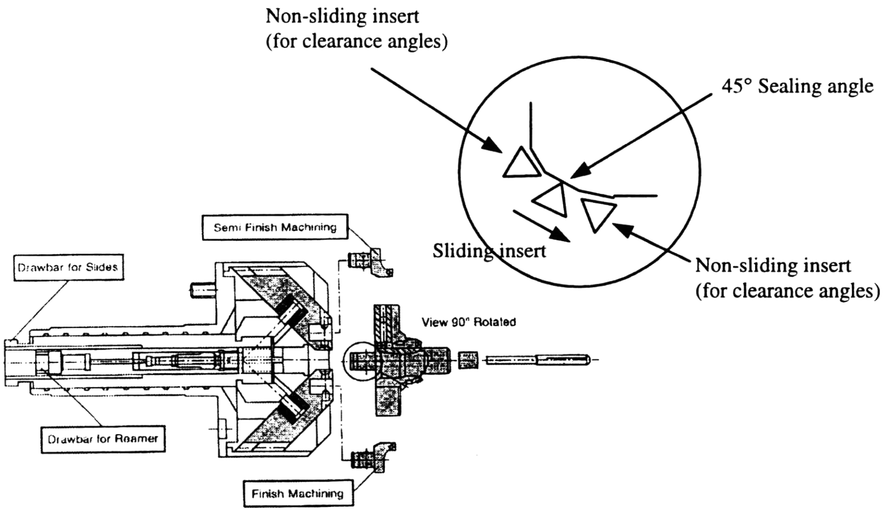


Figure 4-4 Generating Head

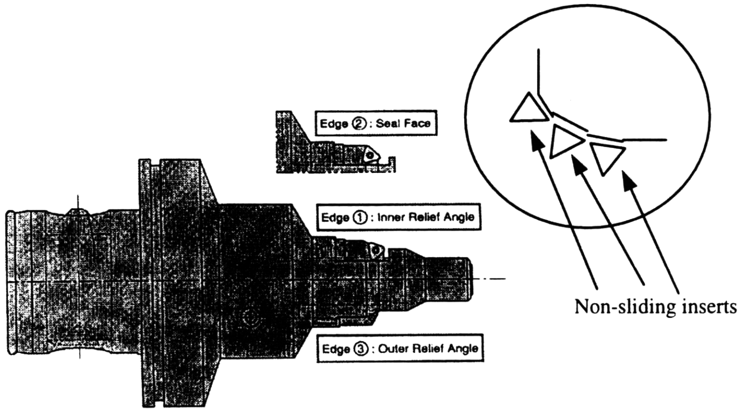


Figure 4-5 Plunge Head

4.2.3.2 Machine uptime effects

Similar to tool-life, issues arise in the PFMEA that relate to machine uptime. Team members will discover that due to product or process design there will be areas where failures are likely to cause long or frequent machine downtime. Similar to tool-life these issues need to be addressed immediately outside of the PFMEA process. Machine uptime analysis is best aided by input from the machine tool supplier and extensive benchmarking of other machining lines built by the same machine tool company.

Valve seat machining- One machine v. Two machines: one example of excessive machine downtime

As mentioned before, valve seat machining is a very complicated process. In addition to the complicated physics of cutting the seats, the cylinder head must be positioned in a complicated angle to allow the tools to access the intake seats. The head must then be rotated around to a different angle to machine the exhaust seats. Our machine tool supplier's original process had both the intake and exhaust seat machining located in one operation. The operation contained two separate transfer bars, one for each type of valve seat. These two bars were controlled with one controller. In order to rotate the part between exhaust and intake machining a gantry would pick the part off of the first transfer bar, roll it over, and place it on the second.

By benchmarking several plants where similar equipment from the same machine tool supplier was used, the team discovered that having just one operation posed some problems. We found out that the situation of two transfer bars being run with one controller required very complex logic programming. Because of this complexity, when the gantry between the stations faulted it caused significant downtime due to troubleshooting. For this reason the team decided to split the machines into two operations, use two separate controllers, and have the roll over occur on the automation between the two stations. The machine tool supplier at the PFMEA agreed that doing this would be very simple. It is believed that this separation will result in a much greater uptime for this operation.

The drawback to splitting the machines is that an extra controller will cost added money. Consequently, the tradeoff is being debated among AME management. Although no detailed cost analysis was done, the team estimates that the added cost will be quickly recouped due to a much greater machine uptime.

4.2.3.3 Scrap and repair effects

Scrap and repair are the most common failure modes identified during the PFMEA. This is where having the experience of a machining line supervisor or other worker with machining experience is critical. While scrap and repair are common machining failures, special attention needs to be made to ensure that other areas, such as transportation, are reviewed for other potential failure modes.

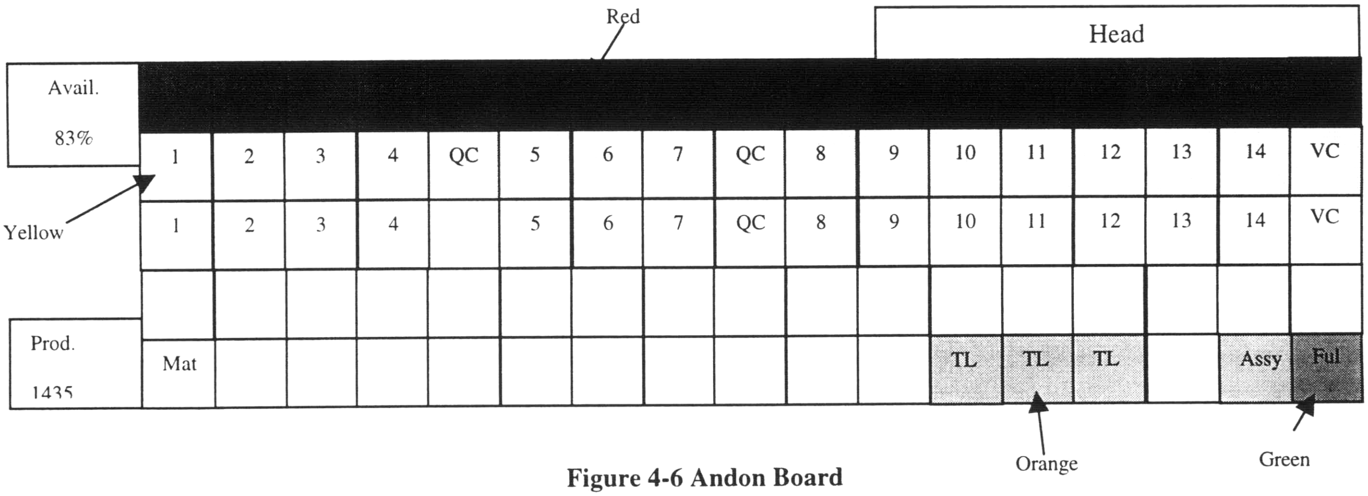
Transportation along Joint Face- one example of a scrap and repair failure mode
The original process dictated that the final joint face machining would occur in station 70 and the cylinder head would be transported along the finished joint face between the subsequent operations. One of the AME team members questioned whether there was potential for damage to the final joint face due to chips or other material being trapped between the transportation rollers and the face. The experienced supervisor confirmed that this failure was not just a possibility, it was a probability. As a result of this analysis the process was changed to transport only on the cover face. A similar concern was raised when the process was modified to locate off of the finished joint face. Some members of the team were concerned that the clamping fixture would leave marks on the joint face. Modifying the head design alleviated this concern. We added material in four locations on the joint face, outside of the sealing surface, from which to locate and clamp.

The PFMEA is the only semi-formal tool used to improve the process at Cobana, and because of this it needs to be taken extremely seriously. As mentioned in previous chapters, 80% of the cost and quality of the part is defined before the end of the Process Definition phase. When used properly, the PFMEA can improve all elements of SQDCM for a given machining line.

While the PFMEA helps define the machine process, the Andon board is the communication link between the process and the operator. The purpose and design of an Andon board is described in the next section.

4.3 Andon board

In order for a machining line to run with 5 operators, the operators need to know the status of the line at all times, from anywhere on the line. As soon as a tool change or quality check is about to occur or as soon as a machine shuts down, the operators have to be informed of this as quickly as possible. All of this information comes to them through the Andon board, an example of which is shown below.



Avail. 83%	1	2	3	4	QC	5	6	7	QC	8	9	10	11	12	13	14	VC
	1	2	3	4		5	6	7	QC	8	9	10	11	12	13	14	VC
Prod. 1435	Mat											TL	TL	TL		Assy	Ful

Figure 4-6 Andon Board

The Andon board is a relatively simple grouping of lights. Each single number corresponds to a specific operation (e.g. 4 is op 40) and the 4A and 7A correspond to accumulator buffers located on the line. A solid red light indicates a machine fault, a solid yellow indicates at tool change is coming up, a flashing yellow indicates a quality check or a tool change is coming up, a solid white light indicates that an operator is present at the machine, and an orange light is a special instruction.

For example, a tool change at operation 70 would be signaled on the andon board as follows:

The yellow “7” would light up, indicating to the operator that a machine in operation 70 needs to be changed. Upon arriving at operation 70 a light on the machine would indicate which station in the operation needed to be changed. If the operator does not get to the station on time (approx. 10 parts) then the red “7” would light up, indicating that the machine has shut down. Once at the appropriate station, the operator will flip a switch which will illuminate the white “7” indicating to the other team members that the operator is at the station performing the tool change. After the tool change the operator resets the machine and all of the lights go off.

In addition to the operation numbers the andon provides the operators with additional information as well. The “avail. %” indicated the percentage of up-time the line is running at since the beginning of the shift. The “Head” light is illuminated when the line is running. The “Prod” shows the shifts production. The “TL” is a call to the team leader that something has gone wrong. The “QC” indicates a quality check. The “Assy” indicates that the assembly line is down, and the “Full” indicates that the buffer between machining and assembly is full.

As mentioned above the andon is a critical source of information and essentially the backbone of a line that is running with five operators. In order to run with a minimal number of people these operators need to be constantly working and need a simple information source which will guide their actions. Without such a source the entire system will breakdown and SQDCM will have no meaning. Because of the critically of the andon, it is very important that the Machine Tool specifications are written to properly explain how the andon needs to be designed and interfaced with the machines.

While the andon board indicates real-time information to all of the operators on a line, sometimes quality issues require past machining information. One way to assist determining the root cause of a quality problem is to design your automation to be first-in-first-out.

4.4 Automation style- FIFO

When quality problems arise on the line it is often necessary to trace the problem back in time. Often downstream parts are inspected for similar quality problems, as are past gauged parts. In this way quality problems can be isolated and root cause can be determined. In order to effectively be able to isolate these problems, the order of production must be maintained throughout the line. Accumulators and buffers are areas in machining lines where order is typically mixed. In these areas, stock usually follows the rule of Last-In-First-Out where the most recently produced part will leave the buffer first, leaving behind parts that were machined before them. In order to prevent this order mix-up it is not only critical that all buffers and automation be designed to use First-In-First-Out but also that parts are continuously cycled through the buffers. In this manner all parts will cycle through the buffers and will remain in the order in which they are machined.

Similar to Automation, another critical Quality element that needs to be addressed by the SE team is their strategy for leak-testing.

4.5 Leak-test strategy

As the name implies, the strategy for leak-testing is to discover air and water leaks after part processing. Typical cylinder heads will be checked for leaks at the end of the machining line as well as after critical machining processes such as valve seat machining. From a CPS perspective this type of checking is value added, as it protects one's down-stream customer from receiving defective material from processes that are not 100 percent robust. However, there are types of checks that are not consistent with CPS. These checks are the ones that occur when a customer needs to verify the incoming quality of the part they receive from their supplier. According to CPS these are wasteful checks because of their redundancy. A customer should be able to expect that their incoming quality is 100 percent and should not consume resources checking this quality. The cylinder head team is designing a redundant leak-testing machine right after the first operation, Operation 20. Although this test does not reflect the strategies of CPS it appears that it may be very valuable. Given the casting suppliers inability to guarantee 100 percent quality on their incoming cast heads, it is important that defective heads are removed from the system as soon as possible. Below is a description of the issues involved and how this related to the team electing to have the casting supplier perform cubing on the foundry floor instead of Cobana performing it in the engine plant.

Cubing in-house versus at the foundry decision
After a cylinder head is cast and the sand cores are removed that make up the water jacket, it must be cubed. The process of cubing removes the risers, gates, and excess flash from the cast head as well as serves to machine the head to make it into a discernable rectangle or "cube". This process of machining the head also uncovers voids in poor castings. These voids will often cause water jacket leakage that results in a scrapped head.

Our casting supplier humbly explained that they needed to perform cubing on their floor because their process was not robust enough to ensure that heads would not leak. Without the cubing, they explained, they had no method of properly checking the head for presence of voids.

Proponents of having cubing done on our floor in Brazil stated that allowing the casting supplier to perform the cubing on their floor eliminated the incentive to improve their process. The attempt to encourage kaizen was thus prevented.

A cost analysis was done in an attempt to make the decision more objective, however the validity of the numbers were questioned due to the fact that most of them came from the casting supplier. As to be expected, the analysis indicated that it would be cheaper for the Cobana to have the casting supplier perform the cubing.

In the end this decision required a vote from the platform team steering committee, a group of engineering, manufacturing and finance managers on the program. They ultimately decided that the benefit of receiving less scrap from the foundry was worth the removal of the incentive to perform kaizen.

4.6 Operator responsibilities

Operator responsibilities are essentially defined with the vision of running the line with 5 people. Listed below are the responsibilities of operators at Toyota, followed by the section in this thesis where the responsibility is discussed:

- Tool changes (Section 3.4)
- All quality checks (Section 3.8)
- Minor machine fault troubleshooting (Section 4.3)
- Minor preventative maintenance
- Kaizen activities

The extent of machine troubleshooting and preventative maintenance is typically defined as a line between the inside and outside of the machines. All activities that can be performed outside of the machine are done by operators, such as resetting the tools from a control panel; the rest of the activities, with the exception of tool changes are performed by skilled trades. This delineation is appropriate for the vision because it allows operators to quickly address problems that take short time to solve and leave the more difficult, longer problems to the people with greater machinery skills.

Kaizen has not been discussed much in this thesis, but it is so common that it is taken for granted in the Toyota culture. Kaizen is the Japanese word for "continuous improvement" and it is the culture by which *everyone* continuously attempts to make their jobs easier and more efficient. As part of the operators daily activities, they will engage in kaizen activities in order to improve their machining or assembly lines. While the platform team has not yet formally defined the operator's roles and responsibilities it is important for the team to understand the vision required to have a CPS plant. In order to effectively run a line with 5 people these operator responsibilities listed above are required and most likely will be formally defined as such in the near future.

4.7 Summary

This chapter focused on the elements a SE team must focus on during the Process Definition phase of a new engine program. It explained the trade-offs between different datum locating schemes and how, upon selection of a scheme, the machining process can begin to be defined. The process can then be improved using the PFMEA workshops.

These workshops were described in detail, including how to set them up, how to run them, and what are some typical improvement results. These results clearly show first-hand the benefits of using the PFMEA process. The last parts of the chapter tied in other design considerations a team needs to incorporate into their process improvement. These consist of andon and automation design, leak test strategies, and operator responsibilities. These supporting elements are critical to be able to implement a robust process. By having the entire team understand these requirements, a lean process can be designed which will serve as one pillar of the CPS plant.

While the last two chapters focused on what tasks needed to be addressed by management and the SE teams, the next chapter focuses on when they need to occur. This chapter gives the timeline for the Process Definition phase.

5 SE Team Timeline

The figure below shows an ideal timeline for the Process Definition phase. Many of the tasks are self-explanatory and are covered in earlier sections of this thesis. Others need a little clarification.

Month 1 represents the start of assembling the AME team. This team assembly occurs before the Process Definition phase, which in the timeline begins in Month 4. Benchmarking in Month 2 consists of trips to existing engine plants to learn about successes and failures with their machining processes. From this benchmarking, the AME team can develop a preliminary design of their machining process which they can include with their request for quote. Once the machine tool suppliers are selected, the SE team needs to meet to do a preliminary process review in order to ensure everyone understands the baseline machining process. At this point the team can begin making improvements to the process.

Other points of clarification: the Strategy Definitions that are listed refer to the strategic management level decisions discussed in Chapter 3. As indicated, these should occur early in the Process Definition stage, if not before. The Departmental Buffering Strategy was covered in section 3.7. This refers to the specific task of determining one's buffers between operations.

	Month 1	Month2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month
Assemble AME members	▨									
Train in platform team in CPS		▨								
Benchmarking		▨								
Bring in Org. Development Consultants		▨								
Bring in Lean Mfg Consultants		▨								
Preliminary Process Design			▨							
Request For Quote for Machine Tools & Castings				▨						
Prototyping of Components				▨						
Material Handling Strategy Definition					▨					
Buffer Strategy Definition					▨					
Tooling Strategy Definition					▨					
Gauging Strategy Definition					▨					
Prototyping of Engine						▨				
Machine Tool Partner Selection						▨				
Department Layout Workshop						▨				
Preliminary Process Review						▨				
Plant Wide Layout Workshop							▨			
PFMEA							▨	▨		
Perishable Tooling Partner Selection							▨			
Tolerancing Workshop								▨		
Departmental Buffering Strategy									▨	
OK to Tool										

Table 5-1 Process Definition Timeline

6 Developing a Lean Culture during the Process Definition Stage

This chapter focuses on the culture of the platform team and how this culture helps or hurts the acceptance of the vision of running a machining line with five people. Culture is often overlooked when attempting to implement TPS in a plant and it is truly the most important piece. Without an understanding and acceptance of the value and power of the floor operators, any lean production system will fail.

Culture is even more important when attempting to design a lean product. The platform team members are the ones who are designing all of the systems and processes and without a full acceptance of the CPS vision, the entire vision will falter.

The platform team has two additional challenges to developing a CPS culture. The first is that platform team was comprised of members from 36 different countries. This diversity brings a wealth of new perspectives and ideas, however, it also brings many different preconceptions about how a plant should be designed and run. For example, some cultures value extreme hierarchy and believe that the word of the boss is final. A culture like this is the antithesis of what CPS, with its extensive operator empowerment, is trying to achieve. The second challenge is that the team is physically separated. In order to foster the teamwork necessary to facilitate a CPS design the team should ideally be co-located. While the platform director tried hard to co-locate the team, he was unsuccessful. But despite these two difficulties, the platform team has made a great deal of progress in improving the teams culture.

This chapter will first define the platform teams culture and then describe the ramifications of this culture. It will then make recommendations to improve it and will also discuss the progress that the team has already made to improve their culture.

6.1 Cultural Analysis of Platform team

This section will look at the culture of the Cobana platform team as a whole and how this culture contributes to the acceptance of the Toyota as a benchmark. Specifically, it will look at the culture through the Ed Schein framework of artifacts, espoused values, and basic assumptions, and will demonstrate a need for outside assistance in order to assimilate into the Toyota culture.

Schein defines artifacts as "all the phenomena that one sees, hears, and feels when one encounters a new group with an unfamiliar culture" (Schein, 1992). Less obvious are one's espoused values, which are values that are shared and understood by the group as a whole but are not readily apparent to outsiders. Only by understanding the artifacts and espoused values can one uncover the basic assumptions of the group, which are usually unconscious assumptions that are not challenged or changed. These form the foundation for the culture and explain many actions and activities that occur within it. By understanding organizational actions at this level, one can understand how to influence and improve an organization. Cultural analysis of the platform team brings to light an organizational deficiency and shows how intervention by an outside consultant should help solve it.

The first artifact that is noticed on the team is the dichotomy in the interaction between its members. On one hand, all of the groups are organized into Simultaneous Engineering teams (SE teams) that contain members of both manufacturing engineering and design engineering. On the other, the manufacturing engineers reside at a different location than the design engineers. Although the platform management attempted to get them co-located, the effect is still divisive. Within specific product teams, all of the manufacturing engineers reside in a shared open cubical area. However, supervisors of these teams have separate single cubicles and are allowed preferential parking. Breaking the dichotomy is the director of the engine program, who truly appears non-hierarchical and open. He is regularly seen wandering around the work areas, performing "management by walking around", talking to engineers and managers alike about issues and problems that exist.

Another clear artifact is the platform team's decision-making sessions. These meetings are extreme consensus building sessions where pros and cons of each alternative are described and debated with passion. Oftentimes either important data is not brought to the meetings, or pro's can not be quantified or challenged. There is not clear evidence as to why this occurs, but when it does, the meeting will end unsuccessfully and the decisions will be tabled until later. Sometimes these meetings will be repeatedly tabled and the SE teams will have to present their pros and con's to the steering committee, so that upper management can vote on the way to proceed.

Another clear artifact is the representation of 36 countries on the platform team. The "melting" of these different cultures provides many different perspectives on how the plant should be designed.

Several espoused values are voiced by the director and echoed by his subordinates. The first is openness. The director shows that he lives by this by his constant search for feedback during his regular walks. He demonstrates his willingness to listen to suggestions from everyone and strongly encourages his staff to do so as well. This openness forms the foundation of the decision making process: all sides need to be listened to before a major decision can be agreed upon. Consensus building also plays a factor in these meetings and often lead to unresolved disagreements and the tabling of the issue at hand.

Another strong espoused value is the director's directive to design all of the processes to be exactly like Toyota's, unless one can prove that their design is superior. This runs into direct conflict with the value of creativity, which is a strong part of the auto manufacturer's culture. Many employees quietly complain that copying Toyota "prevents [them] from being creative".

The artifacts and espoused values can be understood to describe some basic assumptions about the culture of the platform team. The direction to "copy Toyota" creates an extreme discomfort among the members of the platform team who really do not understand Toyota and Toyota's processes. These members see their strength and value added at being creative, and the apparent stifling of creativity removes all of their weapons, leaving them vulnerable. This vulnerability is part of what causes the entrenchment during the decision-making processes. Design engineers find protection in using classic design engineering values such as tight tolerances and strict adherence to functional design, while manufacturing engineers find protection in loose tolerances and consideration of manufacturability of the part. What results is a standoff between the two parties and the tabling of the decision. This uncomfortable newness further inhibits the decision making process because it makes it very difficult to place a value on certain benefits. For example, one benefit of a proposed design may make the operator of the line feel a greater ownership of the line. While it may be argued that ownership will lead to better quality, there is no way of putting a concrete number on the value it brings. These debates are further complicated by the different values that team members from 36 countries bring. Examples like the one above explain why many times pros and con's can not be properly evaluated and oftentimes decisions are tabled. Furthermore, we see how uncomfortable newness can destroy a culture of openness by causing its members to become entrenched in their familiar mindset.

6.2 Ramifications of the platform teams culture

The ramifications of this culture are severe, as the director of the engine program and many members understand that it is impossible to be successful by just copying a system that may be somewhat incompatible with the platform team's system. A complete understanding of the benchmarked system is required so that it can be modified as required to fit the team. To this extent the platform team has identified the need for an outside consultant who is knowledgeable about the Toyota Production System. This individual needs to teach the Toyota Production System to the entire team. In addition, his teaching should be able to provide comfort to the team and allow them to come to an understanding of the value of certain intangible benefits such as ownership. In short, this consultant needs not only to impart knowledge, but in doing so also needs to improve and streamline the deficient decision making process.

Another requirement is for the platform team to get assistance improving team dynamics. This was first attempted through "Town Hall" meetings and through work with the organizational development group at Cobana, but these internal resources were not sufficient. Currently the platform team is utilizing external consultants who specialize in organizational development. These consultants are helping to improve teams skills, decision making processes, and communication skills. In the five months that the consultants have been working, the team has noticed quite a lot of progress, but "much more needs to be done"[24].

The two types of consultants mentioned above are key members of a functioning SE team. Their role as experts is discussed in the next section.

6.3 SE Team model and Role of experts in implementing lean

Work by Klein (1994) forms a useful framework for looking at the SE teams and their need for experts. While typically reserved for plant operations, this framework can be extended to the product development process as well. Shown below is the model for a SE team, what Klein refers to as a "Small Business Team Model". The craft model which is depicted is the model commonly referred to as "throw the work over the wall" organization of product development. In this organization each function is separate from the other (process engineering, product engineering, quality, etc.) and operates independently. Each function has a large depth of expertise, however, their optimized designs for their functions are seldom the optimized team design. This organization results in a great deal of rework and waste.

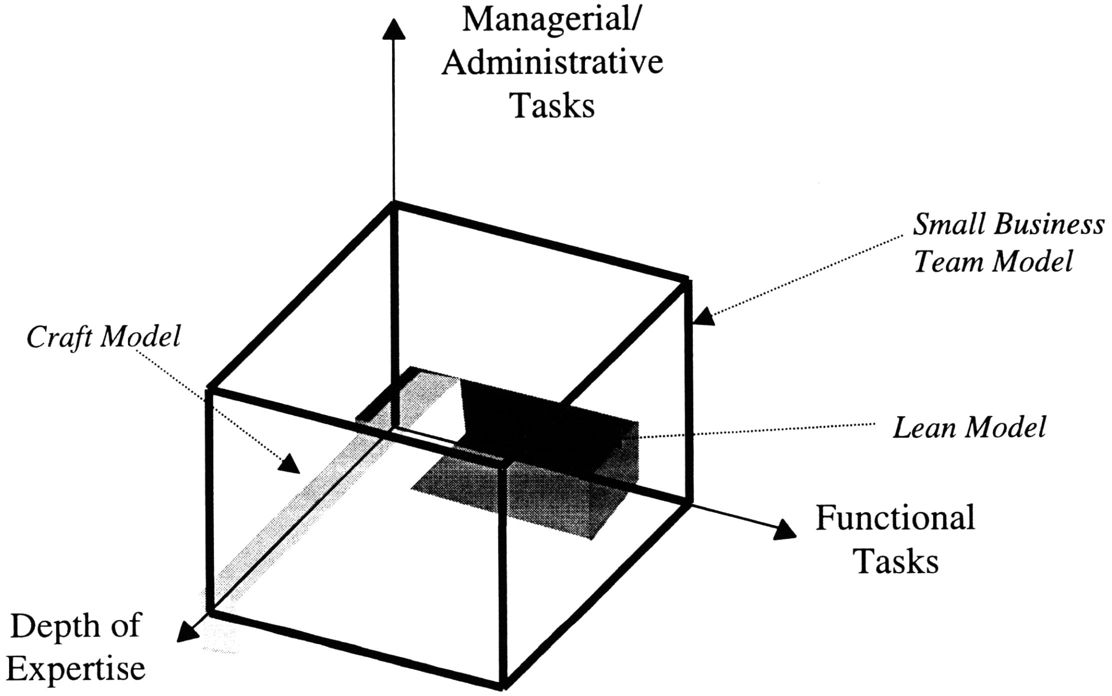


Figure 6-1 Klein's Small Business Team Model

The lean model describes the organization that the platform team is emulating. In this situation, all functional tasks are represented in the SE teams. Each team member brings

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[24] Interview with platform director, April 12, 1998

their representative expertise, which is extensive, but not as extensive as the craft product development people's expertise. The platform team realized that these lean SE teams did not have the depth in experience in lean manufacturing design that was required to develop a CPS plant. Similar to the lean model in the figure above, the SE teams lack of expertise does not allow them to fill the Small Business Team cube. Klein notes that this lean model requires the use of additional expertise in certain instances for special skills the team is lacking. These expert resources are what fills the cube and are what the consultants bring to Cobana's platform teams. By being shared by each of the SE teams, the required expertise in TPS and organizational development is being provided to the teams. As such, the SE teams now reflect the fully functioning Small Business Team Model.

6.4 Summary

The platform team has a great deal of challenges ahead of it, in order to make a team which will share the same vision of how the CPS plant should be designed and how to go about doing so. Issues of different cultures and functions and the general discomfort with designing something that is not fully understood all pose significant hurdles. The good news is that the platform management recognizes their deficiency and have implemented the appropriate consultants to aid the team's culture. These consultants complete the Small Business Team model, and should work to develop effective SE teams. In addition to the consultants, the leadership of the platform team is critical to support the vision of the CPS plant. Without this support, a vision will result in no action.

7 Conclusion

The engine program's platform team began the product development process with no past program from which to benchmark the design of a lean plant. To provide the missing guidance they developed the vision of running a large machining line with 5 people. This stretch goal by Cobana's existing plant standards formed the guide that directed all of the actions of the platform team. From this vision and past experiences came the key elements that needed to be focused on, which are presented in this thesis. This thesis described the management issues that need to be addressed as well as one team's specific issues during this Process Definition phase. Each section described the differences and tradeoffs between the traditional way of operating and the lean way. Shown below is a summary of all of the tangible benefits, as well as references to appropriate parts of the thesis where the topics are discussed.

Element	**Traditional Plant**	**CPS Plant**	**Reference**
Small machining line, # of people	8-12	2-3	
Large machining line, # of people	15-20	4-5	
Labor Hours / engine	5.7[25]	2.6[26]	
Automation Style	LIFO	FIFO	Sec. 4.4
Level of Automation	Equal to CPS	Equal to Traditional	
Gauging Strategy	Complex, Unbalanced	Simple, Balanced	Sec. 3.8
Information system	Varied, complex	Andon board	Sec 4.3

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[25] Cobana's current (without Mexico production)

[26] Current Toyota benchmark

Inventory level	~5 days	Avg 2 hrs +safety	Sec 3.7
Inspection	Full time operator	Part-time operator	Sec 3.10
Layout (ft^2)	600,000	400,000[27]	Sec 3.6
Machine Tool Specs	~20 pages	Hundreds of pages	Sec 3.1
Material Handling	Conveyors, Fork-lifts	Point-of-use	Sec 3.5
Operator Responsibilities	Single Tasked	Multi-tasked	Sec 4.6
Tolerancing	Strict on non-functional dimensions	Loose on non-functional dim.	Sec 3.9
Tool management strategy	Block changes	In-process changes	Sec 3.4

Table 7-1 Summary of Traditional vs. Lean

Included in the trade-off discussions were examples from real team experiences describing successes and difficulties that the team encountered. These experiences should be useful to frame the context of the thesis as well as provide future teams with some understanding of the challenges involved.

Chapter 6 discussed the culture of the platform team and presented it as the greatest challenge for the team. Culture is one challenge that all teams will face attempting to adapt to lean design, and should not be taken lightly. The engine team has invested considerable time and money into working with consultants to ease the transition and the team feels that they have made a lot of progress already. However, there is still a "long way to go."

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[27] Normalized Toyota benchmark

This thesis attempted to provide the design guide for a CPS plant that did not exist prior to the Process Definition phase of this engine program. The questions that now exist are how to improve this guide and how to disseminate its information to future teams.

With respect to dissemination, this work is already being read by a future engine platform team at Cobana, and as such should provide much valuable information and guidance. One of the first things that any platform team should engage in is procuring the appropriate expert resources. One improvement that this future platform team has incorporated is the use of a "lean" consultant earlier in the program. This consultant is already working to install the culture that is critical to the design of a CPS plant. Eventually Cobana should be able to develop the expertise in-house and not be dependant on consultants to guide the lean design.

With respect to future improvements to this guide, the consultant is taking the many tasks listed in this thesis and forming an "operating plan" which will dictate all of the tasks that need to be addressed in designing a CPS plant. This document will provide the design guide that the current platform team was missing, and will give better design guidance than the simple vision of a "5 person machining line". The operating plan will also be a living document that will be passed on and improved program by program. This document will provide an instrument for diffusing the information to all future programs and for continually improving their designs.

Areas for future research are in establishing a guide for subsequent phases of the engine program and for studying better ways to guide lean plant design. Although the consultant should provide some guidance for design of these phases, the primary design is still a "5 person machining line". This subsequent guide should provide detailed analysis, such that all future teams can fully understand the foundation behind the design. This analysis should be similarly incorporated into the operating plan for use in future programs.

Lean plant design is currently being looked at through different frameworks, one of which is axiomatic design. Axiomatic design needs to be simplified in order to be a practical design guide, but it is one area that has a lot of potential for providing a straightforward design. This design would systematically incorporate all of the elements of the Toyota Production System.

Appendix A- Axiomatic Design for Factory System[28]

HI - Human Infrastructure
L&BS - Leveled & Balanced Schedules
VAA - Value-Added Activities
RCIC - Robust, Capable, and In-Control Processes

Customer Attribute	*Functional Requirement*	*Design Parameter*
HI: Recruiting & Hiring	Manpower requirements meet factory needs.	Clear definition of manpower requirements.
	Worker skills meet factory needs.	Clear definition of worker skill requirements.
	Manning flexibility meets factory needs.	Workers can perform multiple functions.
HI: Role / Responsibility Clarity	Factory systems enhance role / responsibility clarity.	Factory systems that enhance role / responsibility clarity.
	Factory systems that provide clear communication channels.	Area is provided that displays day-to-day plant activities and responsibilities.
	Physical extend of responsibility is defined.	Physical boundaries.
	Physical extent of management responsibility is defined.	Buffers which define bounded segments which align with management structure.
	Physical extent of worker responsibility is defined.	Workstations are clearly marked and bound the line worker's responsibility.
	AME system enhances role / responsibility clarity.	A plant development system that enhances role / responsibility clarity.
HI: Performance Feedback	Factory design facilitates performance feedback.	A factory design which facilitates performance feedback.
	Layout facilitates performance feedback.	Areas which allow clear communication of performance.
	Performance metrics effectively measure performance.	Performance metrics that effectively measure performance.
HI: Policy Focus & Deployment	Layout facilitates policy focus & deployment.	Area for communicating policy focus & deployment.
	AME system facilitates policy	AME system that facilitates

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[28] By Jamie Flinchbaugh and Ryan Blanchette

	focus & deployment.	policy focus & deployment.
HI: Employee Involvement	Factory system supports employee involvement.	A factory system which supports employee involvement.
	Layout supports employee involvement.	Area which supports cross-functional team activities.
	AME system utilizes employee involvement.	An AME system which utilizes employee involvement.
	AME system utilizes plant involvement.	A process which encourages plant input at all stages of plant development.
	AME system utilizes input from all team members.	A process which involves all team members in decision making.
HI: Employee Development	Factory system supports employee development.	A factory system which supports employee development.
	Layout supports training.	Area for training near the line which supports *x* workers.
	A method for developing employees to improve explicit knowledge of the factory system.	Workshops which utilize a cross-functional team to explicitly design the factory system.
L&BS: Capacity & Process Planning	Factory system is flexible to meet unknown market needs.	A factory system which is flexible to meet unknown market needs.
	Line is flexible to meet unknown market needs.	A line which is flexible to meet unknown market needs.
	Lines are flexible to support volume changes.	A line which is capable of volume changes.
	Lines are flexible to run mixed model.	A line which is capable of running mixed model.
	Lines are flexible to change vehicles.	A line capable of building different vehicles.
	Material handling is flexible to meet unknown market needs.	A material handling system which is flexible to meet unknown market needs.
L&BS: Production Planning & Scheduling	Production planning & scheduling is capable of maintained leveled & balanced schedules.	A production planning & scheduling system which maintains a leveled & balanced schedules.
	The scheduling system can maintain leveled production.	A scheduling system which provides leveled production.
	The scheduling system maintains workload balance through product variety.	A process to develop schedules which maintain workload balance.
	The scheduling system communicates our schedule to our suppliers.	A method to communicate our schedule to suppliers.
	The scheduling system	A method to communicate our

	communicates our schedule to the plant floor.	schedule to our plant floor.
L&BS: Material Flow Planning	Use minimal amount of material to support a factory system in the most efficient method.	A material flow which uses the minimal amount of material to support a factory system in the most efficient method.
	Material path is most efficient.	A material path which is most efficient.
	Each part's production path can be identified.	A defined path for each part from dock to line.
	Eliminate waste in part travel.	Minimal part travel distance in plant.
	Eliminate waste in material handling resources.	Minimal amount of material handling resources.
	Minimal material level to support production.	The minimal material level which can support production.
	Minimal amount of purchased material to support production.	*x* hours of purchased material at *y* location within part path.
	Minimal amount of WIP to support location.	*x* hours of WIP to *y* location.
	Material display is most efficient.	A material display method which is most efficient.
	Workstation material is clearly displayed and easily accessible.	Workstation clearly displays material.
	Eliminate waste in dunnage use.	Dunnage & use which results in minimal waste.
	Easy identification of distinct parts or features.	Plant-wide color code scheme.
VAA: Identify & Eliminate Waste	Eliminate factory system waste.	Methods for eliminating factory system waste.
	Eliminate waste of walking.	A method for eliminating waste of walking.
	Eliminate waste of processing.	A method for eliminating waste of processing.
	Eliminate unnecessary facility resources.	A method which determines appropriate facility resources for each operation.
VAA: Practice Sharing	Effective way to share factory system design.	A method for sharing factory system design.
VAA: Standardized Work	Factory system supports standardized work.	A factory system which supports standardized work.
	Workstations allow any process configuration.	A standard workstation design.
	Workers need to know their position within job cycle time related to takt time.	A method for indicating position within job related to takt time.
RCIC: Robust	Processes need to be robust.	A method for developing robust

Product & Process Design		processes.
	Process can be continuously reconfigured or improved.	Flexible process.
RCIC: Quick Problem Detection & Correction	Factory system supports quick problem detection and correction.	A factory system which supports quick problem detection and correction.
	Quality can be detected in-station.	A factory system which supports operators detecting quality problems.
	Operators have sufficient lighting to identify quality problems.	Level and location of workstation lighting.
	Facility features are quickly identified.	Factory-wide color code scheme for facility features.
	Quality can be fixed in-station without affecting throughput.	Factory system which allows quality to be fixed in-station without affecting throughput.
	Entire line does not shut down when stations are shut down.	Buffer size and location which allow stations to shut down without affecting throughput.
	Quality problems can be communicated to available resources.	Andon system.
	Quality problems can be fixed in-station quickly.	Resources which fix quality problems in-station quickly.
	Tools for replacement and repair are easily accessible.	Location and display of tools for replacement & repair.
RCIC: Total Productive Maintenance	Line stoppage due to maintenance problems is minimized.	A system which minimizes maintenance problems.
	Locations of essential systems are accessible for maintenance.	Layout designs access to essential systems.
	Maintenance is quickly notified of problems or potential problems.	Andon system.
	Maintenance is notified of preventive maintenance tasks.	A system for tracking and indicating preventive maintenance tasks.
	Tools for preventive maintenance are easily accessible.	Location and display of tools for preventive maintenance.

Appendix B Partial listing of Toyota's Machine Tool Specs

- How to program the Andon is specified
- Man/Machine Interface is specifically laid out- they have a picture of what the MMI will look like- color of lamps, location of switches and buttons. Goal is to give machine tool vendors the opportunity to improve without increasing Toyota's spare parts.
- Specification on how the tool change interface works
- PM specifications: A PM schedule, lubrication map, suggested parts replacing time. Toyota does not ask for Mean Time To Failure!
- Drill detector- all detectors are manual touching of drill
- Blind holes- too shallow or too deep checked
- Tools need to be able to be cycled once for quality checks
- 4 button stop procedure required for all machine tool stations

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