THE DESIGN AND IMPLEMENTATION OF MATERIAL AND INFORMATION FLOW FOR MANUFACTURING SYSTEMS

by
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ABSTRACT

Production systems are characterized by complex interactions between elements, both human and mechanical, with the goal to accomplish certain high-level manufacturing objectives. In order to ensure that the decisions made and the actions taken during the design and implementation of production systems are aligned with all of the objectives, a structured approach must be followed. In developing this structured approach, the axiomatic design methodology is applied, which provides the means for creating a hierarchy of system design objectives (what to do) and solutions (how to do it).

From this conceptual design process, a Production System Design and Implementation (PSDI) Path is presented here. The PSDI Path guides the design through a series of steps in creating a successful physical manufacturing system environment in terms of the original high-level objectives.

Defining the material and information flow in the system is a critical part of the PSDI path. Based on the steps in the PSDI Path and the design hierarchy, a procedure for constructing the material and information flow in the production system is developed. To aid in the design of material and information flow in the manufacturing system, a manufacturing system modeling environment is developed as the tool for visualizing and communicating the flow in the manufacturing system design.

KEYWORDS: *Lean Manufacturing, Value Stream Management, Manufacturing System Design, Production System Design, Cellular Manufacturing, Axiomatic Design*

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1 Introduction

1.1 The Third Industrial Revolution

In his book The Structure of Scientific Revolutions, Thomas Kuhn presented the notion of progress in science as a series of revolutionary events followed by widespread development of the new concepts. Major advancements in all areas of technology such as biology, computer science and manufacturing tend to follow a progression through three phases, from a state of relative disorder toward structured development. These scientific revolutions begin in "crisis phase." [Kuhn, 1970] The conditions in society create a strong need for improvement in a particular area of technology. The Industrial Revolution followed this model, and the crisis phase in America can be traced back to the need for industry to support the development of a stronger military in the late 18^{th} century. The crisis phase is characterized by a vast difference between the perceived needs of society and the lacking state of technology.

Technology then emerges from this crisis phase into a state of "revolution," during which scientific progress begins to close the gap between technology and societal need. An innovative concept will spark this transition and will lead to progress in a specific direction. Almost 3 decades after Thomas Jefferson proposed a contract for 4000 muskets to be manufactured with interchangeable parts, a system of inspection with standard gages was introduced at the Springfield Armory. The gages would later prove to be the fundamental tool behind the early success of the industrial revolution in the U.S. [Hounshell, 1984]

With the goal now attainable, the innovation spreads. This phase of "normal science" is characterized by the spread of not only the new technological concepts, but also the core knowledge base behind it. Researchers follow a more structured path toward observing and understanding the technology progression, followed by iterations of experimentation and learning. The technological change diffuses throughout society until it becomes common practice. The Industrial Revolution, for example, is still happening today, and it has already changed the course of society in ways that could not have been imagined at its onset. Similar examples of scientific revolutions came from the introduction of relativity and quantum mechanics, theories that have given rise to the nuclear energy and microelectronics revolutions, respectively [Hawking, 1988].

Figure 1.1 is an interpretation of this model of scientific revolutions. Progress, used here to mean either the perceived needs of society or the advancement of science and technology, is plotted versus time. Two curves are shown. The dashed line represents a changing society and the solid line represents how progress in science and technology lags behind societal need.

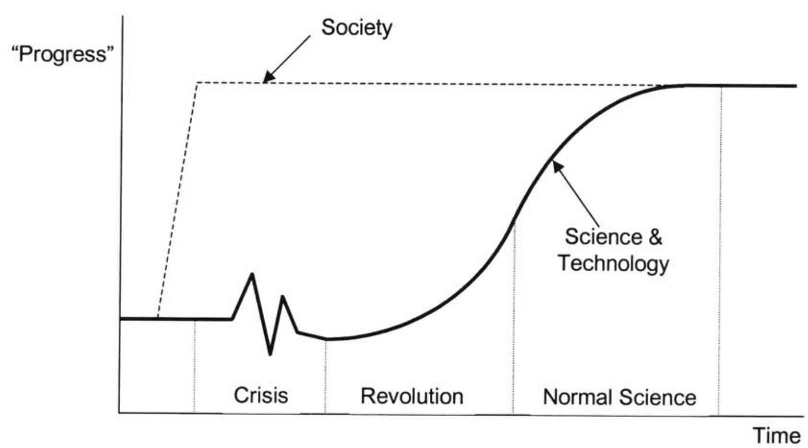


Figure 1.1
A model of the progress of scientific revolutions relative to societal need [adapted from Kuhn, 1970]

The industrial revolution has happened in waves. The first wave described above, resulted in the ability to produce field serviceable products in large quantities, thanks to interchangeable parts. During the second wave of the industrial revolution, many sought a way to improve the quality of transportation by manufacturing automobiles efficiently. With Henry Ford's assembly line at Highland Park in 1913, that goal was achieved, and the concept of mass production spread throughout the manufacturing world over the past century. [Hounshell, 1984]

The third wave of the industrial revolution has been progressing since the end of World War II. The crisis phase first took place in Japan, which, after the close of the war was in a state of economic distress. The existing mass production approach to manufacturing no longer suited the needs and constraints of Japanese industry. In other words, the assumptions behind the success of mass production were no longer applicable in post-war Japan. The success of the Ford system lied in its ability to minimize cost factors by efficiently producing in large quantities. [Hounshell, 1984] Huge amounts of capital investment and seemingly infinite market demand supported this approach to mass production for decades preceding WWII, but post-war Japan saw different requirements for its production systems. [Cochran, 1994]

This state of economic stress is the environment in which the Toyota Production System (TPS) was born and developed into a fierce strategy of eliminating waste- in all forms. Later coined *Lean Manufacturing* by the MIT International Motor Vehicle Program (IMVP) and Machine that Changed the World [Womack, Roos, Jones, 1990], the Toyota Production System has been the innovation, or the "technology" in our third wave of the industrial revolution. Just as Ford's mass production system revolutionized manufacturing through the 20th century, TPS will re-revolutionize the discipline of Production System Design.

Using Kuhn's term, this thesis exists in the context of the "revolution" phase of the 3rd wave of the industrial revolution and is intended to support the ongoing research in the Production System Design Laboratory at the Massachusetts Institute of Technology in Cambridge, Massachusetts. Based on the advancements in the design, implementation and operation of production systems there is a motivation for the development of knowledge and tools that enable those who interact with production systems to ensure that it is designed properly; production systems must be designed as systems.

THERE IS NO UNIVERSAL PRODUCTION SYSTEM DESIGN SOLUTION

Rather than think of a particular production system design, such as TPS or "lean" manufacturing as a ubiquitous solution that accomplishes any objective, it is necessary to design production systems based on the explicit manufacturing and business strategic objectives. No production system design can be thought of as universal; the optimal production system design varies with industry, product and time. [Suh, Cochran, Lima, 1998] Therefore, it is necessary to approach the design of production systems as a methodology that links the manufacturing and business strategy to the specific goals and solutions of the production system design.

MOTIVATION

The need for a structured approach to Production System Design (PSD) and a PSD Framework to provide the necessary tools stems from the realization that:

(a) *The production system plays a significant and increasingly intensive role in the business, the industry and market, and society.* Manufacturing and production is only one individual element of an entire business, but it may be a company's strongest competitive weapon. In terms of all of the sources of competitive advantage (price, quality, leadtime, reliable delivery, product/process innovation, product/process flexibility, field service) the decisions made in manufacturing system design, implementation and control will determine the level to which the business will succeed.

(b) *The production system is a complex engineering system that is composed of technical elements of all natures, both human and mechanical.* Every decision in production system design, implementation and control involves an interaction of objectives and solutions. The PSD Framework provides the means for communicating the choice of solutions and guaranteeing that the solutions chosen will independently achieve all objectives. [Cochran, 1998] This approach to system design is especially important for production systems in which humans are playing a critical role in performing both direct labor tasks and system control tasks (both long-term and short-term control). It is common for systems with this characteristic of human participation and supervision to be misdirected by the decision-makers. The decision-makers tend to get trapped in traditional modes of thinking (mental models), and often the best solutions to problems are hidden by the structure of the system [Senge, 1990].

(c) *The production system is a system that is designed and operated with the impetus of achieving simultaneous goals.* There exist several frameworks and methods that classify a complete set of system objectives, from which a subset can be derived that describes the specific goals of a particular production system [Hayes, Pisano, 1996].

The PSD Framework provides clear definition of objectives (what to do) and physical solutions (how to do it). "The goal is to provide a means for communicating and deploying a system design to numerous people. The Framework uses the axiomatic design methodology to prevent confusion and the blind and rote application of rules." [Cochran, 1998]

DEFINITION OF A MANUFACTURING AND PRODUCTION SYSTEM

A *manufacturing system* is a group of physical objects arranged to transform raw material into finished product. [Black, 1991] These physical objects include machines, tools, material handling equipment and people. Along with the raw material, a manufacturing system also requires information (customer orders, current system status), capital (money, equipment, fixed assets) and energy (labor, power, support resources) as inputs. The total output includes finished product, information, waste and profit.

Manufacturing systems are affected by internal and external disturbances, and can be evaluated by measuring its intrinsic parameters (cost, time, quantity, area). The customers of the manufacturing system are those who receive finished product from the system.

A production flow *value stream* is a way of mapping a manufacturing system. "A value stream is all the actions (both value-added and non-value-added) currently required to bring a product through the main flows essential to every product: the production flow from raw material into the arms of the customer." [Rother, Shook, 1998]

Depending on how the system boundaries are defined, the customer of the manufacturing system value stream may be a retailer, a distribution channel, a processing plant, or a downstream function in the same plant. Important attributes of the system are defined by the system's functional requirements (formally defined in chapter 3) and are measured by the system's performance measures. A formal model of the control of manufacturing systems is presented in section 5.3.

The production system includes the manufacturing system and all functions required for the support, operation and control of the manufacturing system. Maintenance, engineering, human resources, accounting, sales and marketing are examples of resources that are part of the production system. A sub-function of the production system is the performance measurement system, which acts as a control mechanism for the manufacturing system. The set of variables being measured, along with the chosen target values, will determine the type of system that exists. In other words, a production system with a purely cost-based performance measurement scheme will be very different from a production system with performance measurement scheme that rates production cost, quality and lead time. [Cochran, Kim, Kim, 2000] Figure 1.2 shows a graphical representation of production systems. [adapted from Cochran, 1994]

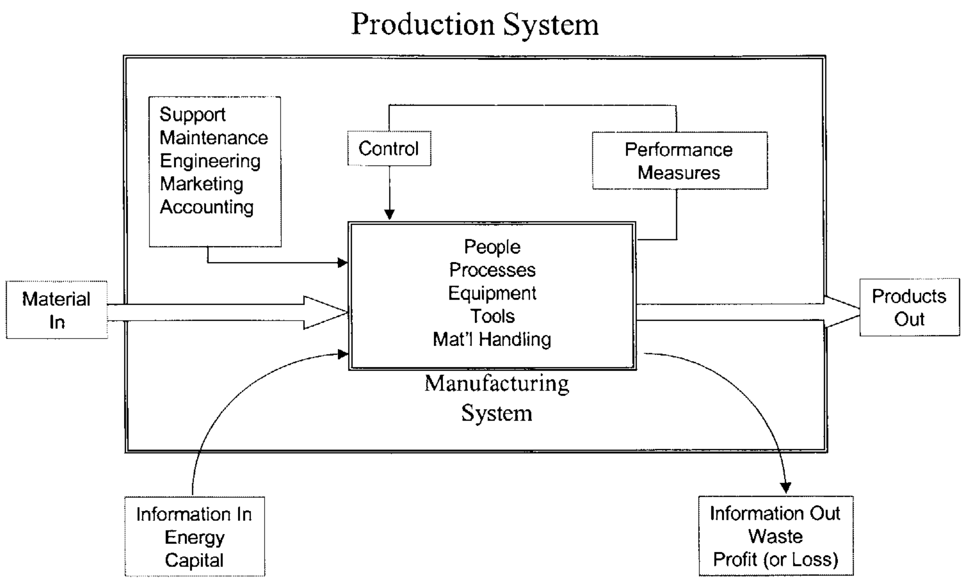


Figure 1.2
A graphical representation of production systems

Production System Design presents a significant challenge to those involved mostly because of a single characteristic: the human element. To fully define the structure of a production system, one must consider the role that humans play. A set of characteristics of human systems, [from Senge, 1990] include:

1. *Structure influences behavior.* Not all system responses are the fault of external disturbances or an individual's decisions and actions. Most system responses are determined by the functional structures of the system (e.g., human resources and performance measurement). This phenomenon of human systems is modeled in the Beer Game simulation in which a system will exhibit strikingly similar responses when operated by different individuals [Sterman, 1992].

2. *Structure in a human system is subtle.* "*Systemic structure* is concerned with the key interrelationships that influence behavior over time. These are not

between people, but among key variables." In a production system, this may include processing times, information transfer delays and reliability rates. "It is very important to understand that when we use the term 'systemic structure' we do not just mean structure outside the individual. The nature of structure in human systems is subtle because *we* are part of the structure. This means that we often have the power to alter structures within which we are operating." [Senge, 1990]

3. *Leverage often comes from new ways of thinking.* Because of limited focus, people often overlook their ability to change the system. "More often than not, we do not perceive the power [to alter structures within which we are operating]. In fact, we usually don't see the structures at play much at all. Rather, *we just feel ourselves compelled to act in certain ways.*" [Senge, 1990] New ways of thinking about how to design and operate production systems will provide greater advancements than trying to optimize the existing faulty system design.

IMPROVEMENTS FROM A SYSTEMS PERSPECTIVE

In designing and managing complex systems, it is critical to view change from a systems perspective. Each decision in the design, implementation and control of production systems should be derived in terms of the objectives of the system. Problems must be solved at the root cause in order to avoid wasteful optimization efforts. In the decision-making process, keeping a narrow view of a part of a system will lead to the optimization of particular operations, rather than the optimization of the overall system. It is important to define *value* from the viewpoint of the *customer*. What is the customer willing to pay for? Is it possible to eliminate all the operations that do not add value, rather than spend resources optimizing wasteful areas?

For example, systems that have been designed properly will have minimal waste. Operations will be linked closely to their downstream customers, quality levels will be consistently high and delays in throughput will be consistently low. A system that has not been designed, but has been *optimized* will show signs of waste. [Shingo, 1989] For example, final quality checks, expensive material handling systems and large levels of inventory are all examples of "improvements" attempting to compensate for fundamental problems in the system design.

TPS has demonstrated its ability to eliminate waste and make effective systems improvements. The notions of eliminating non-value added operations and eliminating problems at the root cause level serve as tools to support the focus of banishing waste. In production systems, waste comes in several forms [Cochran, 2000]:

Forms of Waste in a Production System

1. OVERPRODUCTION (producing too much and/or too early)
2. INVENTORY (to hide problems between operations)
3. TRANSPORTATION (moving parts)
4. EXCESS PROCESSING (unnecessary steps)
5. DEFECTS (quality problems as seen by the customer requiring rework or scrap)
6. MOTION (unnecessary worker movements)
7. WAITING (workers waiting for machines or parts)

Production systems must be designed with simultaneous goals in mind. All elements of the system must be operating in harmony to ensure that all performance criteria are being optimized. This design process is by no means easy, but it is the most important theme in all of this research. It is a challenge that will be faced by all those involved with manufacturing system design, implementation and control. The research presented here has been developed in attempt to better enable success in manufacturing by aligning the approach of production system design with the theme of making systemic improvements.

How do we understand the interaction between all of the areas of the production system (people, equipment, flow, etc.)? To answer this question, it is critical to understand design objectives (what to do) vs. design solutions (how to do it). For every physical system parameter or object, there is a set of objectives that it should be accomplishing. First, these objectives must be developed by decomposing the high-level goals. Then, solutions must be designed for the objectives, and finally, the solutions must be implemented as physical system objects. A framework for performing these three tasks is presented in chapter 4 as the Production System Design and Implementation (PSDI) Path.

The trend in the implementation of lean manufacturing over the past decade has been to observe and implement particular "lean concepts" as seen in TPS. These misdirected efforts are not complete systems implementation, and many researchers have pinpointed this issue as the reason for failure in manufacturing. A system design must accomplish the high-level system goals and conditions. [Suh, Cochran, Lima, 1998] An effective system design cannot be assembled from a set of low-level elements of best-practices. [Spear, Bowen, 1999] [Cochran, 1998]

1.2 Problem Statement

The design and implementation of a manufacturing system must be approached from a systems perspective as defined above. In particular, the design of the material and information flow in a system must be matched with the high-level objectives of the business. In order to ensure that these objectives are met and embodied in both the conceptual and physical designs, there should be a set of tools developed to aid in the design and implementation of these flow systems. Prior work has been done to develop a complete set of production system functional requirements (objectives) and design parameters (design solutions) to apply to a production system design.

1.3 Research Objectives

As part of the approach to the design of manufacturing systems from a scientific and systematic perspective, a framework will be constructed for discussing the interaction between strategy, objectives, design solutions, constraints, performance measures and implementation. The specific tasks necessary for successful design and implementation of manufacturing systems will be summarized in the creation of the Production System

Design and Implementation (PSDI) Path. The design of material and information flow in the system, a critical link between the high-level system objectives and the detailed subsystem design, is expanded upon. In the context of existing research on Production System Design, an *approach* to the design of material and information flow in manufacturing systems will be proposed. As part of this approach, requirements for the design of material flow systems and information flow systems are identified. It will be shown that the material and information flow in a manufacturing system must be implemented as an integrated structure. To form the language of this discussion, a model of material and information flow in manufacturing systems will be shown. This model will serve as a tool to visualize flow in a system, as well as communicate the system design at the material and information flow view of the system. Addressing the material and information flow in the manufacturing system design is a critical part of the design process, in which the high-level objectives are translated to the low-level design requirements of the detailed subsystems.

2 Scope, Flow and Focus

Throughout the course of this thesis, some themes will frequently be used to explain the characteristics of production systems and production system design. In order to better understand the physical nature of manufacturing systems and the procedure of designing and implementing production systems, it will be helpful to create abstract notions of how the pieces of a system fit together.

2.1 Levels of scope

The first theme that is important in conceptualizing the design of production systems is the notion of *levels of scope*. Analogous to a birds-eye view of the physical system, the level of scope defines the resolution of detail that we are considering at a point in time. At the very detailed, "microscopic" level of scope, the most intricate details of individual workstations are being considered; at this level of scope, the exact layout, timing and automation content of each machine becomes significant in designing equipment for the system. At a higher level of scope, for example, when analyzing entire distribution channels, simply modeling an entire plant as a single entity with attributes defining key variables may suffice. Various levels of scope that will be discussed here include, in order of most detail to most general, the operation level, the workloop level, the cell level, the linked-cell level, the plant level and the value stream level. In the following chapters, it will be shown that production system design involves the transition through all levels of scope, in consonance with the functional requirements and design parameters of each level.

2.2 Flow

Visualizing *flow* in production systems is a critical aspect of production system design. Of the two types of flow, material flow is usually the easiest to see by simply following parts as they move through the system. In seeing material flow, it is important to notice discontinuities in the flow, because of buffers, queues, waiting times, mis-sequencing of parts, parallel paths and reversed flow (e.g., parts that are moved backward or upstream in the plant for rework or repair).

Information flow may be harder to visualize than material flow. As material is flowing from the suppliers, through value-added processing and to the customers, information traverses through the system in the opposite direction, away from the customer and toward the suppliers. Whether or not the information is taking a clear and logical path through the system is another issue, but the information is moving opposite the material flow nonetheless. Information comes in different forms in different systems. Batch and queue manufacturing systems typically rely on forecast data and a central production scheduling department (sometimes using Material Requirements Planning (MRP) scheduling) to provide production information to the processes in the plant. In lean manufacturing systems, information is transferred to the process directly upstream, giving exact demand requirements in frequent time intervals. Material is exchanged for information in the correct mix and volume, thus providing the customer process with reliable supply, just-in-time (JIT). This idea has been called a *pull system* and is also a critical aspect of TPS [Monden, 1990]. In watching the information flow from the customer to the supplier, it is important to notice at which point in the information stream the customer order integrity is lost. What types of delays and discontinuities are there in the information flow?

One of the caveats of the Toyota Production System is that the flow of material and information throughout the system is clearly visible, which helps in reducing the waste in the system.

2.3 Focus

The design of the production system across all levels of scope must remain focused. The design objectives must be based on the needs of the customer and the characteristics of the products, processes, industry and market of the production system. To understand the notion of *focus*, consider the task of adopting a manufacturing strategy. A subset of the overall business strategy, the manufacturing strategy is the approach that the manufacturing system takes to maximize business objectives and create a competitive advantage for the company. A typical manufacturing strategy will define what sort of focus the system must take to maximize customer and shareholder satisfaction and maximize profits with low risk. Manufacturing strategies can only be determined on a case-by-case basis, since every decision involves weighing several environmental variables simultaneously. The following characteristics will play a role in determining the manufacturing strategy [Hayes, Wheelwright, 1984]:

1. Product characteristics (material cost, development burden, size, life-cycle production volume and production volume flexibility)
2. Process characteristics (investment, capacity and capacity flexibility, technology innovativeness, cycle time, changeover time, product flexibility, predictability in future process characteristics)
3. Customer characteristics (distribution requirements, demand average and deviation, customization and product differentiation, method of information transfer from customers, quality requirements)
4. Market/Industry characteristics (market size, market share, life-cycle length, predictability in future market/industry characteristics)

Based on all of these characteristics (although some of them may be negligible compared to others), a proper focus strategy can be devised. Figure 2.1 shows the types of focus decisions that can be made based on characteristics of the system. In designing the system, a set of attribute/decision factor combinations will be chosen as the focus. One combination will be the primary focus of the system, while some other combinations may have secondary influence.

Attribute		Individual Customers	Markets (Customer Groups)	Industry (Competitors)	Product	Process
		Decision Factor				
Demand Volume	Mean	++			++	
	Variation	+	+		++	
Cost	Fixed (Overhead & Investment)				+	+
	Variable				+	
Life-cycle duration		+	+	+	+	+
Physical attributes (size, speed, location, resources)		+	+		+	+
Product differentiation & customization		++			+	+
Quality (specification or output)						+
Reliability or predictability of any of these characteristics		+	+	+	+	+

TO READ THIS CHART:

"The flow of the production system may need to be focused based on the *<attribute>* of the *<decision factor>*."

++	Common strategy
+	Possible situation
	Unlikely situation
	Invalid attribute for this decision factor

Figure 2.1
Focus Decision Matrix

For example, a typical effective strategy in production system design is the customer-focused linked-cell system [Black, 1991]. The flow through these systems is designed based on customer demand volumes, maximizing customer satisfaction through superior quality, response time and reliability. Another example of a production system design is the process technology focused design. These types of systems can be seen in innovative industries with very short life-cycles in product and process technology, such as the semiconductor industry. Because of long development lead times and costs, the production systems are designed to accommodate process and product flexibility.

Designing production systems with focus gives companies a significant competitive advantage in the market [Lee, 1992]. As will be seen in the Production System Design and Implementation Path presented in chapter 4, the focus decision is one of the early steps in the production system design and implementation process, and all subsequent decisions are fully dependent on it. The focus decision will have a large impact on the approach to designing the material and information flow in the production system. Without a clear definition of focus in the production system design, it will be ineffective, regardless of the level of effectiveness of individual components of the system.

3 Axiomatic Design

In chapter 1, it was shown why it is important to approach the design and implementation of production systems based on a standard methodology. When analyzing complex systems it becomes difficult to conceptualize the design without a tool to relate the physical properties of the system to the original design goals. "Design involves a continuous interplay between *what we want to achieve* and *how we want to achieve it.*" [Suh, 1990] Developing a structure for discussing design goals and solutions is the first step in understanding manufacturing system design. The concepts presented here are a direct application of the work of Nam Suh, The Principles of Design [Suh, 1990].

Axiomatic design is a methodology that is used to translate the goals of a design to the physical implementation of the outcome. Formalizing the design process is an idea that stems from the fact that there exists a tangible notion of the "success" of a design and that there must be specific features of a good design that set it apart from a bad design. The *simplest* design that *independently* translates design objectives (defined by the customer) into physical components is the best design. The two important words here are independent and simple; these two characteristics of a design will be defined by the two fundamental axioms of axiomatic design. The notion of "translating" objectives into solutions is an iterative process of mapping and decomposing the design between different realms of definition, and will be discussed in further detail in the following sections.

Following the process of axiomatic design helps to keep the only the most key features as the driving force of the design during the process, thus producing an effective solution that always performs as desired. In the complex production systems being discussed in this paper, the key to achieving success through axiomatic design is that all design and engineering decisions, from the high-level conceptual design to the specific sub-system and component details all directly evolve from already known design requirements. Each decision on a design feature can be related to a functional goal of the design and every functional goal of the design is developed from the specific desires of the customer. This mapping of design features to customer desires ensures a successful outcome from the customer's point of view.

Axiomatic design is ultimately flexible in how it can be used; it can be applied to any engineering problem. The methodology comes in two parts: it provides instruction for the designer to develop the design details from the design goals, and it defines two guidelines to ensure that the design decisions being made are the best possible choices. Even with these guidelines, axiomatic design does not restrict us from applying the method to any type of problem. Applications of axiomatic design range from system-level design based on business objectives through detailed engineering design based on customer desires and market trends.

3.1 Design Domains

When considering a design, we usually visualize a physical entity that has been created. The design process that resulted in the creation of the product actually steps through 4 domains, which are shown in Figure 3.1.

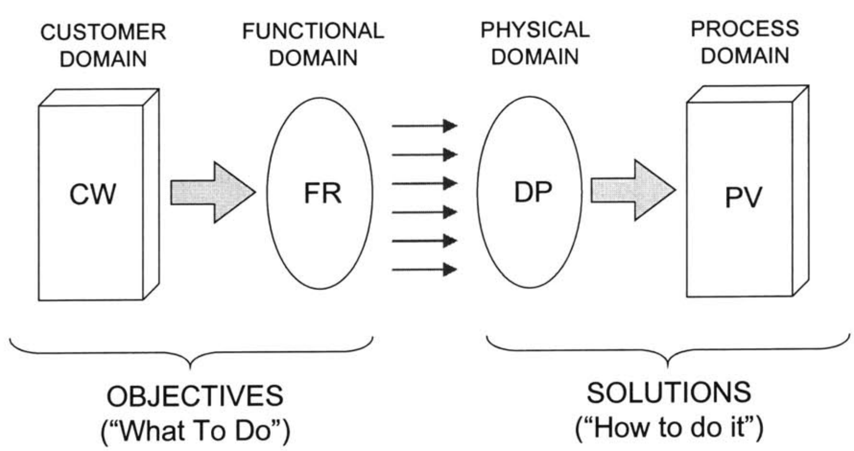


Figure 3.1
The 4 Domains of the Axiomatic Design Process

CUSTOMER DOMAIN

The customer, or the user of the design, should specify what the product will look like. The goal of any design process is, of course, to satisfy the need of the customer. The first step of any design process is to identify the customer "wants." In a typical organization, the management staff along with the marketing team will usually perform this task. It is important to be very general in this task, and to create a set of independent customer requirements that are solution-neutral. In other words, the customer wants domain should not give any pre-conceived notion of a design solution.

The customer requirements can be arranged into a vector of independent statements that will sufficiently define the space of the customer's view of the design. For example, a customer requirements vector for the design of a water faucet is:

$$[\mathbf{CW}] = \begin{Bmatrix} \text{CW1: Deliver water at a comfortable temperature} \\ \text{CW2: deliver water at a comfortable pressure} \end{Bmatrix}$$

These two statements fully specify what it is about a water faucet that the user cares about. These statements are neither dependent on each other nor do they imply any design approach (they are solution-neutral).

FUNCTIONAL DOMAIN

A functional requirement is analogous to a customer want in that it helps us define *what* the design must accomplish. A set of functional requirements, which are derived from the customer requirements space, will create a new space called the *functional space.* The functional space defines the desired output of the product completely and specifically. It becomes the launching point for the conceptual design of the product. "Functional requirements are defined to be the minimum set of independent requirements that completely characterize the design objectives for a specific need. By definition, FRs are independent of other FRs and can be stated without considering other FRs." [Suh, 1990, chapter 2] However, a functional space is not necessarily unique over time, space or across perception of individuals. The functional requirements of a manufacturing system change over time (decades, for instance) [Cochran, 1994], depending on the environment in which they exist (European systems vs. American systems vs. Japanese systems) and depending on the way they are perceived by the designers.

Using the example of the water faucet, the functional space may be defined by the following set of FRs:

$$[\mathbf{FR}] = \begin{Bmatrix} \text{FR1: Deliver water in a temperature range of } 50\,^\circ\text{F} - 150\,^\circ\text{F} \\ \text{FR2: Deliver water at a pressure range of 2psi 5psi} \end{Bmatrix}$$

PHYSICAL DOMAIN

Design parameters are chosen to satisfy the functional requirements. The design is translated from the functional space into the *physical space*, and the physical characteristics of the design begin to be identified. It is through this mapping of functional requirements to design parameters that the creative part of design takes place. Any given designer may select a different set of design parameters to define the physical space, so the design space is not unique. There can be an infinite number of plausible design solutions and mapping techniques. By applying the rules of axiomatic design, the best design solution can be chosen from the set of possible design solutions.

From the vector of function requirements for the design of the water faucet, we may derive a vector of design parameters such as:

$$[\mathbf{DP}]_a = \begin{Bmatrix} \text{DP1: Volume flow rate of water from hot reservoir} \\ \text{DP2: Volume flow rate of water from cold reservoir} \end{Bmatrix}$$

$$[\mathbf{DP}]_b = \begin{Bmatrix} \text{DP1: Volume flow rate of water mix between hot and cold flows} \\ \text{DP2: Pressure of flow through faucet} \end{Bmatrix}$$

Both of these physical domain representations were derived from the same set of functional requirements, and each set of design parameters could result in design solutions that solve the customer wants $[\mathbf{CW}]$. However, one of these two solutions is more ideal than the other, because each of its design parameters is independent of the other. In the section titled "Design Axioms" below, we will analyze these two designs and identify which of the two is a better solution.

PROCESS DOMAIN

Once the physical domain has been defined by the selection of design parameters (DPs), the conceptual idea of the product can be manifested into a physical object. This object or product can be produced and controlled by manipulating certain *process variables.* These process variables (PVs), or control variables are defined in the *process domain*, and are derived directly from the design parameters. The process variables are the levers by which the design parameters are manipulated. The process domain, completely defined by these process control variables, is what the production system designer (or operations manager) has freedom to control. Some process variables are built into the long-term control structure of the system and some can be manipulated via real-time control policy. Each design parameter should be able to be controlled by altering one and only one of the process variables, but this is often impossible in manufacturing systems because of coupling between the design parameters and process variables.

Figure 3.2 shows what the water faucet design looks like in the process domain, based on the 2 different design parameter vector spaces shown above. In design (a), the design parameters are hot water flow and cold water flow. The process variables in this design are hot water valve position (DP1a) and cold water valve position (DP2a).

$$[\mathbf{PV}]_a = \begin{Bmatrix} \text{PV1 : Hot water valve position} \\ \text{PV2 : Cold water valve position} \end{Bmatrix}$$

In design (b), the design parameters are hot/cold mixing level and water flow pressure control. The process variables in this design are mixing flow rate valve position (DP1b), and total flow valve position (DP2b).

$$[\mathbf{PV}]_b = \begin{Bmatrix} \text{PV1: Mixing flow rate valve position} \\ \text{PV2: Total flow valve position} \end{Bmatrix}$$

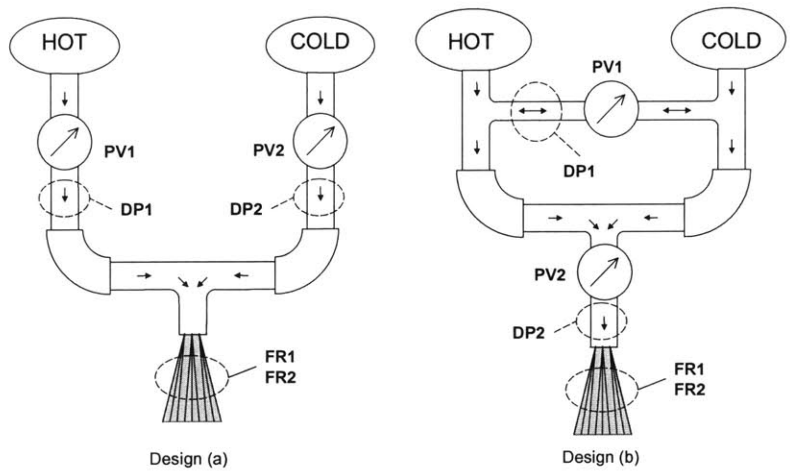


Figure 3.2
Alternative designs for a water faucet

3.2 Mapping and Decomposition

In the example of the water faucet, the design was translated between the four domains of axiomatic design. Customer requirements were translated to functional requirements. Through the creative design process, design parameters were chosen to satisfy these functional requirements. Finally, process variables were selected in order to control the state of the design parameters. In each of these steps, the design underwent a *mapping* from one domain to the next. The design is conceptualized in a different way in each domain, and the 3 mapping steps took the design through each conceptual phase.

In fact, the water faucet was a very simple application of the axiomatic design process. Once the customer needs and functional requirements were identified, design parameters were chosen. These design parameters were so simple that the design was able to be mapped directly into the process domain; no further detailed design was necessary to create a physical embodiment of the design.

In complex design problems, such as production system design, one iteration of these 3 mapping steps is not sufficient enough to provide a detailed explanation of the design. Once the primary customer requirements and functional requirements are chosen, and the design is mapped to the design parameters, the design may not be detailed enough to implement. In cases such as these, the design zig-zags between the functional and physical domains (FR $\leftarrow\rightarrow$ DP) several times, until the design is described with enough detail in the physical domain to be implemented. Mapping is half of this zig-zag process, as the functional requirements, which identify "what" the system design must accomplish are translated into design parameters, which identify "how" the system design will accomplish the "what" through creative selection. These design parameters can then be *decomposed* into lower-level functional requirements by asking "what" objectives need to be met in order to accomplish the "how" identified by the design parameters. Decomposing the DPs into lower-level FRs moves the design back into the functional domain, at a level of finer detail.

These two functions, mapping and decomposition will be discussed in further detail in the context of production system design in chapter 4. By iterating these two functions, the design is manifested in both the functional and physical domains, at all levels of detail. The result of this zig-zagging is a complete hierarchy of design objectives and solutions. From this conceptual design hierarchy, the physical system can be constructed and implemented.

3.3 Axioms

AXIOM 1: THE INDEPENDENCE AXIOM

Axiom 1 deals with the relationship between the functional and physical variables of a design. When mapping the functional domain ([**FR**]) to the physical domain ([**DP**]) , the choice of DPs must be such that a change in one DP affects one and only one FR. Formally, axiom 1 states "Maintain the independence of FRs." [Suh, 1990]

AXIOM 2: THE INFORMATION AXIOM

As discussed above, the definition of the physical domain from the functional domain is not a unique process. Rather, it is a creative process, and therefore different designers will create different [**DP**] vectors. Axiom 2 deals with the selection of the most optimal [**DP**] space. The best design will be a design that satisfies axiom 1 and has the least information content. In design, the information content is the probability that the FR will be satisfied. In other words, if there is a high probability of success (robust products that are easily calibrated to the target), the information content is low. Formally, axiom 2 states "Minimize the information content of the design." [Suh, 1990]

3.4 Design Matrix and Coupling

The functional space, physical space and process space are defined by the vectors [**FR**], [**DP**] and [**PV**] respectively. Axiom 1 states that the relationship between the spaces defined by [**FR**] and [**DP**] must be independent. If we create an equation showing the relationship between [**FR**] and [**DP**], there is an element called the design matrix [**A**] that qualifies the type of dependence.

$$[\mathbf{FR}] = [\mathbf{A}][\mathbf{DP}]$$

The matrix [**A**] will be an *m* x *n* matrix where *m* is the size of matrix [**FR**] and *n* is the size of vector [**DP**]. In a design that is not redundant, i.e., there is the same number of design parameters as functional requirements, the matrix [**A**] will be square.

The elements of the design matrix indicate a dependence relationship between FR_i and DP_j if $A_{ij} = X$. If $A_{ij} = O$, then the corresponding FR – DP pair is independent. If by changing the state of a DP, the state of a FR is altered, then there is a dependence relationship and the corresponding design matrix element is X. [1]

[1] A special case of a design matrix is the non-linear case. Normally, the elements of the design matrix can be modeled as constant relationships, i.e., across the entire range of [**DP**], the elements A_{ij} indicate either dependent (X) or independent (O). In a non-linear design, the values of A_{ij} will vary with [**DP**],

Just as there is a design matrix [**A**] relating [**FR**] and [**DP**], there is a design matrix [**B**] relating [**DP**] and [**PV**]. If the alteration of a process variable affects the state of a design parameter, then the corresponding element of [**B**] is X.

$$[\mathbf{DP}] = [\mathbf{B}][\mathbf{PV}]$$

The design matrices for water faucet design (a) are:

$$[\mathbf{FR}] = \begin{bmatrix} \mathbf{X} & \mathbf{X} \\ \mathbf{X} & \mathbf{X} \end{bmatrix} [\mathbf{DP}]_a \qquad \text{COUPLED}$$

$$[\mathbf{DP}]_a = \begin{bmatrix} \mathbf{X} & \mathbf{O} \\ \mathbf{O} & \mathbf{X} \end{bmatrix} [\mathbf{PV}]_a \qquad \text{UNCOUPLED}$$

The design matrices for water faucet design (b) are:

$$[\mathbf{FR}] = \begin{bmatrix} \mathbf{X} & \mathbf{O} \\ \mathbf{O} & \mathbf{X} \end{bmatrix} [\mathbf{DP}]_b \qquad \text{UNCOUPLED}$$

$$[\mathbf{DP}]_b = \begin{bmatrix} \mathbf{X} & \mathbf{O} \\ \mathbf{O} & \mathbf{X} \end{bmatrix} [\mathbf{PV}]_b \qquad \text{UNCOUPLED}$$

As defined by the independence axiom, design (b) is uncoupled between the functional and physical domains. The X's on the diagonal of the design matrix indicate that each design parameter affects one and only one FR, and equivalently, each FR is affected by one and only one DP. To arrive at a desired state of $[\mathbf{FR}]_{ideal}$, one can alter [**DP**] in a single iteration. Uncoupled designs are examples of acceptable designs, and the simplest design will be the most ideal (the one that also satisfies axiom 2).

$$A_{ij} = f_{ij}([\mathbf{DP}]).$$

So, the coupling of these designs can only be determined over discrete ranges of [**DP**]. If the design is coupled, varying [**DP**] may never lead to convergence on $[\mathbf{FR}]_{ideal}$.

Design (a) is fully coupled because alterations in a single DP affect the state of both FRs; it is impossible to change the state of one FR without affecting the other FR. In order to arrive at a desired state $[\mathbf{FR}]_{ideal}$, the operator must continually iterate on [**DP**] until the current state converges to the desired state. If the design is non-linear, the design may never converge. Water faucet (a) is a coupled design, because the user can not alter a single FR at one time. Whenever one design parameter is changed, both functional requirements change. We have all experienced this coupling between the process domain (faucet controls) and functional domain (water temperature & pressure) in the search for the perfect shower. If we want more water pressure (FR2), then we might turn up the cold water (PV2), increasing the flow of cold water (DP2). But now the temperature is too cold (FR1 is no longer satisfied), so me must increase the hot water level (DP1). In doing so, we have overshot the desired level of water pressure (FR2). So, we must iterate several more times until we converge on a perfect water pressure and temperature. Five minutes later, when there is a lot less hot water in the reservoir, the entire iterative control process must be repeated.

Axiom 1 can be interpreted to mean that coupled designs are too complex and therefore undesirable. In Figure 3.3, the graphical representation of a coupled design shows what happens when coupled systems are controlled. When a single DP is altered by controlling its associated PV, it is analogous to traveling along one of the DP axes in the design space. While moving along the DP1 axis, both values of FR1 *and* FR2 are changing. Similarly, in a fully coupled case, both values of FR1 and FR2 change when moving along the DP2 axis. It is impossible to independently alter one FR.

The intermediate case between coupled and uncoupled is quasi-coupled (also known as decoupled and path-dependent). In a quasi-coupled design, the design matrix is:

$$[\mathbf{FR}] = \begin{bmatrix} \mathbf{X} & \mathbf{O} \\ \mathbf{X} & \mathbf{X} \end{bmatrix} [\mathbf{DP}]_{decoupled}$$

FR 1 is only affected by changes in DP1, but FR2 is affected by changes in either DP1 or DP2. In order to quickly arrive at the desired state of $[\mathbf{FR}]_{ideal}$, the designer can alter DP2 until $FR2_{ideal}$ is reached. This action will also affect the state of FR1. Then DP1 will be altered until $FR1_{ideal}$ is reached. As in the uncoupled case, the desired state of [**FR**] can be reached with a single iteration. However, there is a distinction in the order in which the DPs should be altered. The DP with the most influence on [**FR**] should be altered first, followed by those DPs with lesser influence. Further discussion on this path-dependency problem in production system design can be found in [Carrus, Cochran, 1998]

Figure 3.3 shows the key characteristics of each type of design relationship.

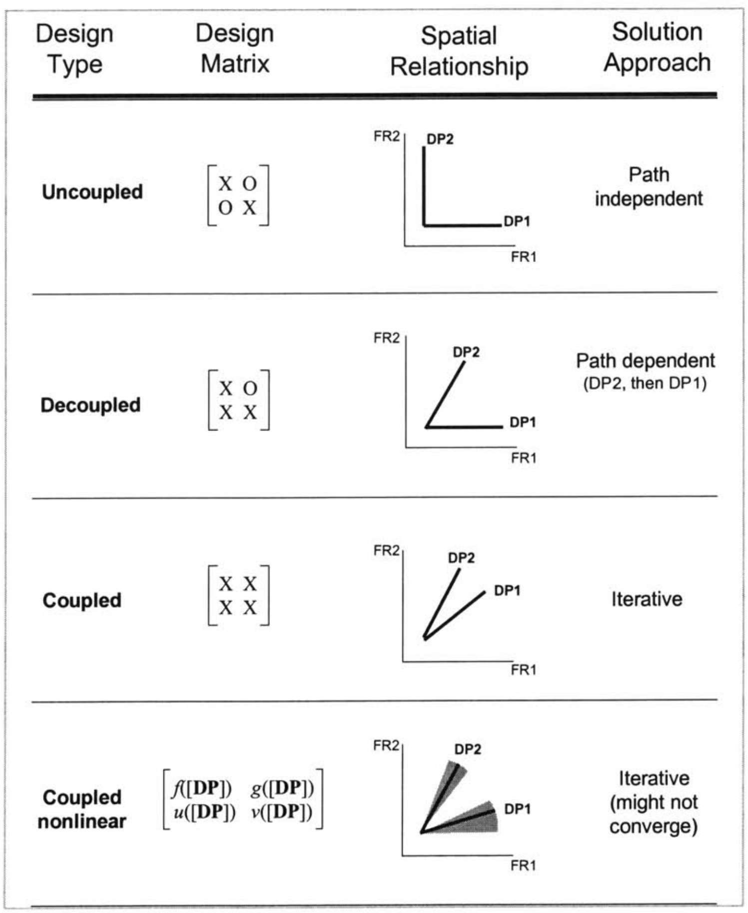


Figure 3.3
Characteristics of the types of relationships between design domains

IMPLEMENTATION OF DESIGNS

Any design problem can be thought of as progressing through the four domains of axiomatic design. The process of decomposing functional requirements and design parameters creates a top-down hierarchy of the design. Once the design has been modeled in the physical domain to such a level of detail that it can be implemented in the process domain, the physical embodiment of the design is created. In the case of product design, this will mean manufacturing the product for distribution to the users. In the case of production system design, this physical realization stage is commonly known as *implementation* of the system design.

There is a theorem that is derived from the independence axiom that discusses the implementation of designs. A design can be implemented if the relationships between the functional, physical and process domains are all uncoupled. Theorem 9, on Design for Manufacturability states "For a product to be manufacturable, the design matrix for the product, [**A**] (which relates the [**FR**] vector for the product to the [**DP**] vector of the product) times the design matrix for the manufacturing process, [**B**] (which relates the [**DP**] vector to the [**PV**] vector of the manufacturing process) must yield either a diagonal or triangular matrix. Consequently, when any one of the design matrices, that is, either [**A**] or [**B**], represents a coupled design, the product cannot be manufactured." [Suh, 1990, ch. 4.10]

The physical realization (implementation) of a design is a step in the design process that is characterized by matrix [**C**]. Matrix [**C**] defines the relationship between the process domain and the functional domain. If matrix [**C**] is uncoupled, then the design is said to be *functionally independent*. The customer is able to optimize a particular functional requirement of the device by altering one and only one control variable.

$$[\mathbf{C}] = [\mathbf{A}][\mathbf{B}]$$

$$[\mathbf{FR}] = [\mathbf{C}][\mathbf{PV}]$$

In order to simplify the design, its components may be *physically integrated.* "Integration of more than one function into a single part, as long as the functions remain independent, should reduce complexity." [Suh, 1990] In general, the most ideal design is one that is physically integrated and functionally independent. In production system design, most components are physically integrated structures; each implementable component (labor tasks, equipment, material/information flow loops, cells, SWIP) is a physical manifestation of several functional requirements.

3.5 Applying Axiomatic Design to Manufacturing Systems

In summary, this chapter has presented a structured approach to addressing design problems. Four design domains were identified. As the design is mapped and decomposed through each of these four domains, a complete hierarchy of the design objectives and solutions is created at all levels of detail. Once the finest level of detail is reached, the design can be implemented.

Chapter 4 will develop the model of the design process in further detail in the context of production system design. In this model, the entity being designed is a *production system*. The customer, i.e., the user of the production system in this case, is the business to which the production system belongs. This "business" customer is the element that defines the highest-level goals of the production system, i.e., the customer domain [**CW**] in the axiomatic design model. Examples of elements that together comprise the business customer are company owners and executives, shareholders and employees. Other factors that help determine the business customer might include such abstract entities such as the environment, societal ethics, the community, the government, the economy and the global village. In other words, all of these factors can have an effect on the goals or objectives of a production system, and thus are treated as customers in the axiomatic design model.

An analogy can be made between the disciplines of production system design and product design. The terminology of axiomatic design applies to both; the application of product design and production system design is compared in Figure 3.4 [adapted from Cochran, 1994].

It is important to note here that the word *customer* will take on a different meaning later on in this thesis. When using the axiomatic design model, the customer is an aggregation of all factors that will determine the objectives of the system. On the other hand, other types of customers are those who consume the *products manufactured by* the production system, i.e., the *value stream customer* (or, supply chain customer). These customers are part of the production system; material and information flows to and from these customers. These customers are analogous to suppliers; material flows from suppliers to customers.

Axiomatic Design Term	Product Design Analogy	Production System Design Analogy
Customer	End User	Business (internal) and Value Stream (external) Customers
Product	Product	Production System
Customer Domain	Customer Needs	Manufacturing Strategy/Objectives
Functional Domain	FRs of product	FRs of system
Physical Domain	DPs of product	DPs of system
Process Domain	Product Settings	Production System Control Variables
Physical Realization	Manufacturability	System Implementation
Feedback Control	Product Performance Criteria	Performance measurements

Figure 3.4
Axiomatic Design terminology when applied to product design and production system design

4 The Conceptual Model of Production System Design

In chapter 3, it was shown how the methodology of axiomatic design can guide a concept through the design process, from the domain of customer requirements to a state of implementation readiness in the process domain. In each domain, the design was described by a vector of statements, viewing the design from a different conceptual vantage point each time. In order to translate the design between domains, two functions are used, mapping and decomposition.

4.1 Definitions

Each domain of the design process (customer, functional, physical, process) can be thought of as a *vector space*. Mathematically, a vector space is an n-dimensional area defined completely by the n components of its vector. A vector space that we are all familiar with is the xy-plane. The xy-plane is a two dimensional vector space that contains an infinite number of vectors. Any one of those vectors, (1,1) for example, fully define the vector space known as the xy-plane. Similarly, our three dimensional world can be thought of as a vector space fully defined by any vector of the form (x,y,z).

What does it mean to define the functional vector space of design? When the design of the water faucet was mapped in the functional domain, a vector [**FR**] was created which fully defined all of the necessary functions of that water faucet. The vector [**FR**], in this case, had two components and therefore defined an abstract 2-dimensional *functional space.* Any function that was not described by the two components of [FR1 , FR2] is outside of the functional space of the design.

When the design was mapped into the physical domain, a new vector [**DP**] was created, which defined a new vector space called the *physical space*. This physical space, also 2-dimensional, identifies all of the important design components that will solve the objectives in the functional space. The design matrix, which characterized this mapping process, links the physical space to the functional space. Since the design matrix is square (2 x 2), we know that the 2 spaces will have the same dimension (2). In the case of an uncoupled design, where the non-zero components of the design matrix are all on the diagonal, the functional and physical spaces will have the same shape (See Figure 3.3). Figure 4.1 shows a visualization of this mapping process. A design with 2 functional requirements exists in the 2-dimensional functional space, and is defined by vector [**FR**]. Each dimension in this space (the sides of the square) represent a functional requirement of the design. The design is then mapped into the physical space by matrix [**A**], which is uncoupled in this example. The axes in the physical space directly correspond to the axes in the functional space.

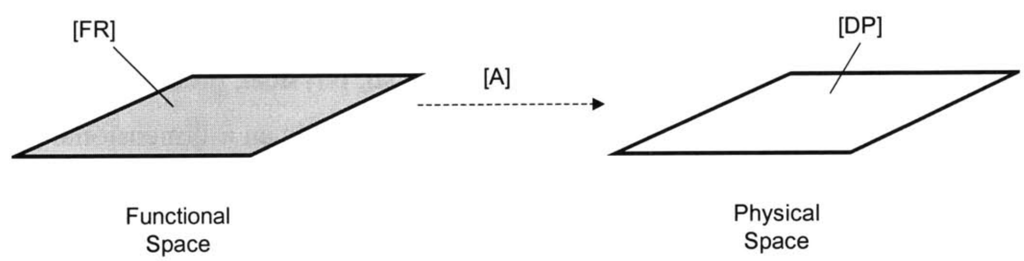


Figure 4.1
Mapping of the design from the functional space to the physical space in an uncoupled design

By decomposition, the design is traversed back into the functional space. However, this new functional space is not the exact same functional space as defined earlier. In fact, it can be thought of as a subspace of the previous functional space. A *subspace*, by definition, is a vector space that does not contain all of the vectors in its parent space but lies entirely within it.

When a design is decomposed from the physical space to the functional space, a new set of functional requirements are created, fully defining the design, but in greater level of detail. This new functional subspace can be translated to the physical space, by the usual mapping process. Similarly, the newly created physical space is a subspace of the level above it. At this new level of detail, the design is completely defined in the functional and physical spaces. In other words, a new, more detailed set of objectives and solutions were derived from those on the higher level. The overall functionality of the design has remained the same; it is still completely defined by the functional space at the highest level. However, the functional requirements were subdivided into more manageable pieces. Figure 4.2 continues the representation of the mapping and decomposing of the design between the functional and physical domains.

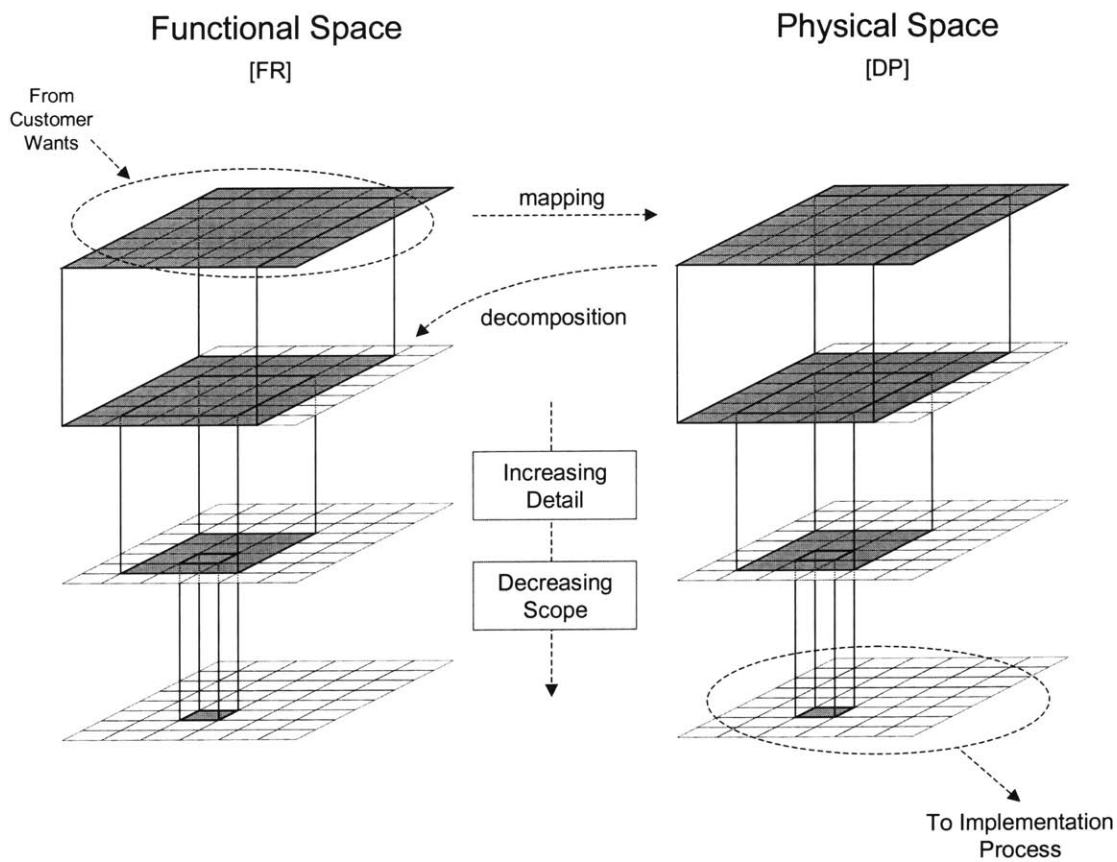


Figure 4.2
THE CONCEPTUAL DESIGN HIERARCHY
Mapping and decomposing of a design between the functional and physical domains

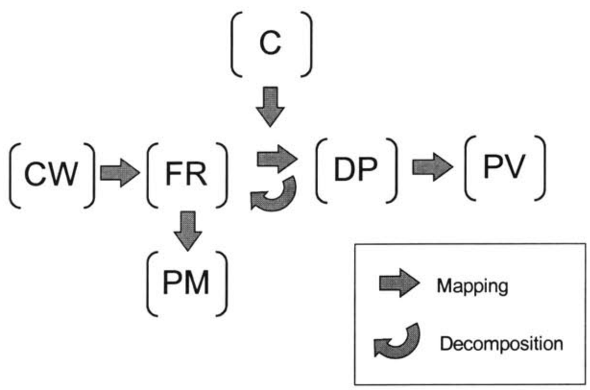
4.2 Design Hierarchy

By mapping and decomposing the design to and from the functional space and physical space, a hierarchy of design objectives and solutions is created. The process of creating this hierarchy was shown in Figure 4.2. Manufacturing system designs will exhibit many levels of detail in the design hierarchy. The design process involves inter-linking the two domains at every level of detail of the hierarchy in the process. These two domains are inherently independent of each other. The design is what links them [Suh, 1990]. However, within each domain, the definition of the design is NOT independent across levels of detail. Within the functional domain, for example, every design objective that is decomposed throughout all levels of detail is dependent on the original definition of objectives at the highest level. Similarly, the solutions in the physical domain are dependent on the previous choices of solutions from higher levels (*and* should be guided by the set of objectives at that level in the functional domain). Design decisions made at the initial or upstream stages of the design process affect *all* subsequent decisions [Suh, 1990]. This notion of dependencies in the design process is critical in managing the design of complex systems, such as production systems. Losing sight of higher-level design objectives or solutions will result in lower-level decisions that are poor.

This characteristic of the very hierarchical design of complex systems becomes important from a manager's viewpoint. In organizations with hierarchical functional structures, teams will often be directed by a limited set of goals, independent of other teams and functions in the system. Subdivision of functions, teams and resources like this is an example of the how the limited objectives of the team are a subspace of the highest-level objectives. These teams tend to lose sight of the total system design, and therefore have the tendency to make decisions contrary to higher-level objectives. These types of systems require that every piece of the organizational structure be aware of its role relative to others in accomplishing the primary objectives. Therefore, communication of the entire design hierarchy to the entire organization is a prerequisite for effective production system management.

4.3 The Conceptual Design Process

Figure 4.3 is a summary of the conceptual design process. Each element in this map is a vector that defines the design in a different domain. *Mapping* and *decomposition* are the two functions that are used to create the design and translate it between domains. These vectors, listed below, play an important role during the design, implementation and control of the system.



Vector	Vector Component	Vector Space
[CW]	Customer Wants	Customer Space
[FR]	Functional Requirements	Functional Space
[PM]	Performance Measures	Control Variables
[C]	Constraints	Limits on Physical Space
[DP]	Design Parameters	Physical Space
[PV]	Process Variables	Implementation

Figure 4.3
The conceptual design process

Viewing designs using this conceptual process helps the system operators, engineers, and managers maintain objectives at the greatest level of detail in a solution-neutral environment. Guidelines can be drawn from this model to guide engineers and managers during the design process. The following two subsections expand on the roles and responsibilities of managers and engineers during production system design. The issues raised here are directly derived from the conceptual design model, which was developed by applying the principles of axiomatic design to production systems. This conceptual model can be applied to *any* system that can be modeled as a production system:

MANAGEMENT APPROACH TO PSD

The manager will typically have influence over factors in the production system at a high level of scope. The highest-level objectives in the production system design hierarchy will be a subset of the overall business objectives, and will most likely be developed by the management team. During implementation and control, the managers will observe the system based on the performance measures [PM] and will make decisions based on the high level objectives and control policies. The responsibilities of the managers of a production system, in terms of the conceptual design process are:

1. Create accurate system objectives (strategy) space [**CW**] that is in sync with internal and external customers, industry, technology, and the business strategy. Be aware of all objectives of the production system, along with any interaction between them. To properly define the customer domain [**CW**], identify the minimum set of objective statements required by all of the system's customers. [Hayes, Wheelwright]

2. Identify & minimize the space of constraints [**C**]. Constraints represent areas of the physical domain that are restricted, limiting the options for creativity in design. The rationale behind any perceived constraint of the system should be questioned rigorously in the attempt to minimize constraints.

3. Manage program for monitoring performance measurement space [**PM**]. The control of the system is manifest through PMs that directly measure system FRs. During the mapping and decomposition steps of creating the design hierarchy, appropriate performance measures are chosen to measure the system properly. The management information system (MIS) must be aligned with these performance measures for effective control of a system. [Lockamy, Cox, 1997]

4. Manage program for implementing the detailed design in the process domain. Once the physical embodiment of the design hierarchy [**FR**] & [**DP**] pairs is created, the system can be implemented in the process domain. The design hierarchy guides the implementation process by ensuring that system objectives (FRs) are met at all levels of scope. In the process domain, certain *system control variables* (SVs or PVs) can be manipulated by managers to achieve the desired state of [**FR**]. The idea of control variables in manufacturing systems is discussed in the subsection titled "Implementation in the Process Domain" on page 50.

ENGINEERING AND OPERATOR APPROACH TO PSD

The engineers, as opposed to the managers, will have influence on the elements of the manufacturing system across several levels of scope. Engineering functions in production system design are typically focused on finding the best feasible solutions and design approaches (DPs) at the lower, implementable levels of the design hierarchy. The operators of the system hold valuable information for the engineers, in that they have the most experience with the manufacturing processes. In terms of the conceptual design process, the engineering teams will take the higher-level functional requirements and information from the operators as inputs and map and decompose them into lower-level design parameters. During this process, the engineering approach to PSD will be:

MAPPING TECHNIQUE

1. Does the choice of DP satisfy the FR?
2. Does the choice of DP affect other FRs?
3. Is the choice of DP optimal in terms of the higher-level FRs?

DECOMPOSITION TECHNIQUE

1. At the next lower level of scope, create a set of FRs, necessary and sufficient for achieving the previous set of DPs.
2. The physical and functional spaces will be decomposed until a sufficient level of detail is reached for implementation. The FRs and DPs that are not decomposed any

further represent the "leaves" of the design and can be implemented to achieve the FRs above them in the design hierarchy.

IMPLEMENTATION IN THE PROCESS DOMAIN

The final step in the conceptual design process is to map the lowest level of the FR/DP design hierarchy to the process domain. In terms of production system design, this step represents the physical implementation of the abstract production system design. The process domain of a manufacturing system design is the complete set of system elements that can be manipulated or controlled. For example, as an overview of the process domain of a production system, the following physical elements represent the control levers of a manufacturing system: machines, direct operators (work teams), support resources (maintenance equipment and personnel, production control, material handling equipment and personnel, supervisors, managers), functional departments (cells, storage areas, shipping, receiving, purchasing). It is difficult to develop a strict definition of the process domain of a manufacturing system, because these systems tend to be complex with an infinite number of "system variables" (SVs) on the physical elements. Rather, it may be helpful to identify the groups of physical elements of the manufacturing system that are analogous to the control variables during implementation in the process domain. These physical elements, or *decision categories* can be thought of as the knobs on the water faucet that the end user manipulates to control the functional requirement settings of temperature and pressure. The following 10 items summarize the types of manufacturing SVs or decision categories, and together form the process domain of production system design [Rosenfeld, 1999]:

Facilities: size, location, focus

Capacity: size of capacity increments, timing of capacity changes

Vertical Integration: direction (upstream/downstream), extent

Process Technology: equipment, automation, scale, flexibility

Workforce & Management: wage policy, skills, job security

Logistics & Material Planning: inventory, production planning, vendor relationship

Organization & Incentives: costing system, performance reporting, organizational hierarchy

Product Development: interface with manufacturing, vendor development

Quality Programs: monitoring, intervention

Partner Management: extent, collaboration

In a manufacturing system, the decision categories of the process domain tend to be quasi-coupled or fully coupled; a single physical element, such as a piece of processing equipment will be an integrated structure that is a manifestation of more than one design parameter. The process domain can be defined as the following:

> The *process domain* of a manufacturing system design is the complete set of system elements that can be manipulated or controlled. Characteristic of the amount of coupling between the process domain and the physical domain, the implementation and control of manufacturing systems will tend to be a path-dependent problem (quasi-coupled) or an iterative problem (fully coupled).

4.4 Beginning the Design of Production Systems

So far, chapters 3 and 4 have presented the theoretical background for approaching production system design. From this basis, a methodology can be created for designing production systems. The approach to PSD will be guided by the basic concepts of axiomatic design. The design effort is to translate and decompose the system objectives into an implementable production system design. Once the production system has been designed, the implementation procedure begins. Implementing production systems requires that each component has been designed in a systems context, and that each component is being controlled properly. Improvements must be based on solving the fundamental cause of problems and resources must be directed with the complete system design in mind.

Figure 4.4 is a map of the path of production system design from design to implementation. On the left side of the diagram, the *design path* is shown. The highest-level objectives are mapped and decomposed into a detailed system design. Objectives (what to do) and solutions (how to do it) cascade throughout the levels of scope of the design hierarchy during steps 1-6 of the PSDI Path. From the manufacturing objectives, the system focus is defined and the conceptual flow design is created, showing the movement of material and information through the manufacturing system. The detailed physical elements of the system are then designed based on this system flow strategy, including the standard work-in-process buffers (SWIP), cells (equipment design, standard work routines), material handling routines and information transfer methods. The design can then be implemented.

On the right side of the diagram, the *implementation path* is shown. The physical components of the system are created. As the physical elements are placed on the manufacturing floor, the flow is buffered with SWIP at first. Each element is improved and controlled using tools to solve fundamental system problems. Direct material and information links between system elements are made. As each element is improved, the inventory buffers are reduced. The first stage of improvements and the associated reductions in inventory involve setup (changeover time) reduction, leveling and pacing production, and establishing predictable quality and time output. The elements can then be linked with pull replenishment. Once the proper flow is established, the suppliers can be linked to the system. Finally, the product design function can be integrated into the manufacturing system. The notion of flow is a theme during this entire process; the system will be designed and implemented with material and information flow in mind.

To expand on the PSDI Path shown in Figure 4.4, chapter 5 will show the existing PSD Framework and how the design hierarchy of manufacturing systems is created. The Production System Design Decomposition is presented here, which is the axiomatic design decomposition of a generic manufacturing system to the most detailed levels. The building blocks of production systems will be discussed in Chapter 6, where an object-oriented model is developed to characterize the components of a manufacturing system. Material and Information Flow can be modeled with these basic elements. Chapter 7 will expand on the PSD framework and its specific applications to material and information flow design. The design requirements that pertain to flow are identified and tools are developed to guide the process. In Chapter 8, the PSDI Path and the specific design tasks discussed in Chapter 7 will be applied in a case study project involving the redesign of an automotive component production system.

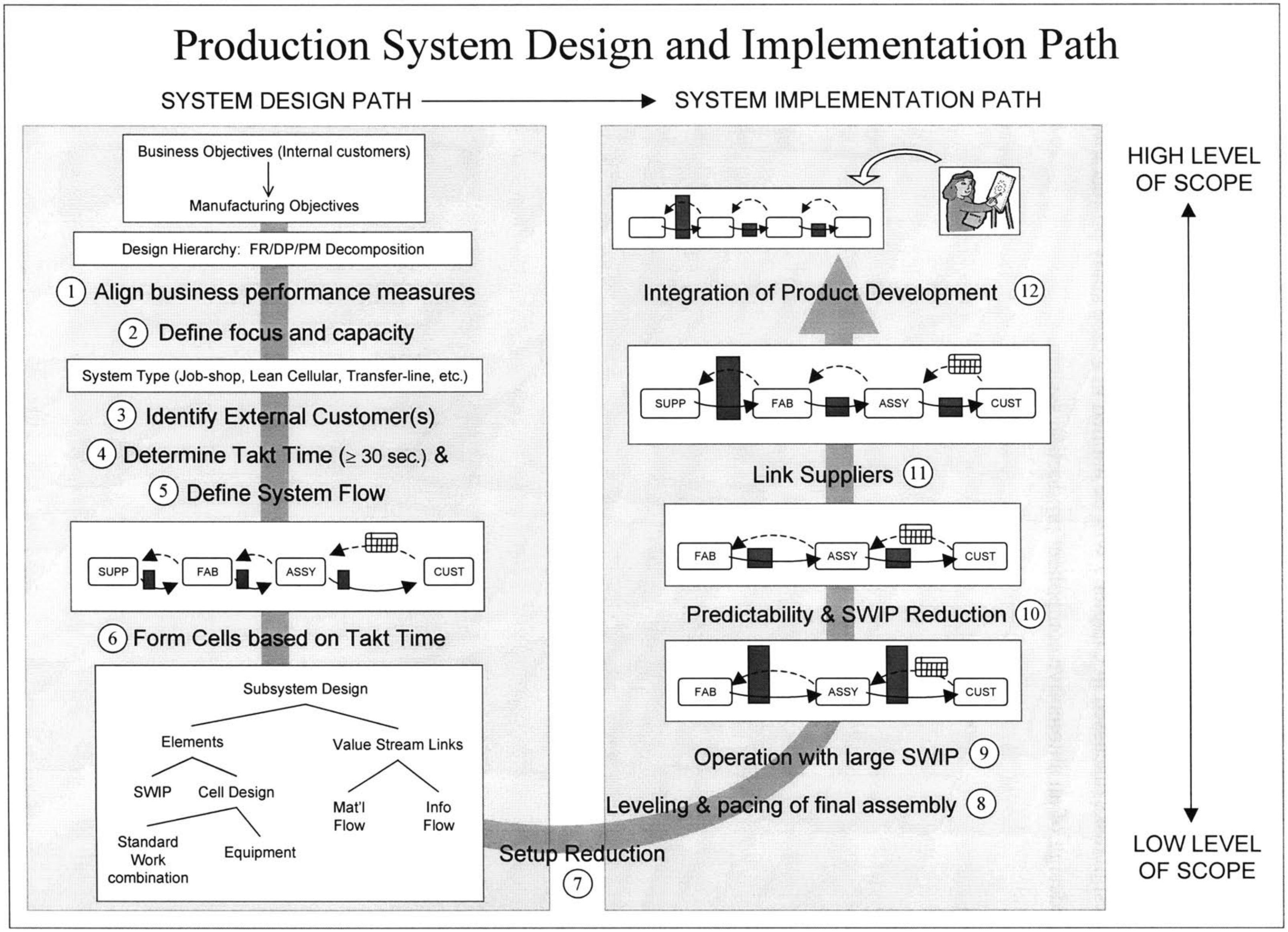


Figure 4.4
The Design and Implementation (PSDI) Path for Production Systems

5 The Production System Design & Deployment Framework

Much of the discussion in this chapter represents prior work in the development of the Production System Design and Deployment (PSDD) Framework. Some of the text here has been adapted from [Suh, Cochran, Lima, 1998] and [Cochran 1999]. This chapter is to serve as an overview of the Framework, noting how its components are applied during the Production System Design and Implementation (PSDI) Path shown in Figure 4.4. The PSDI path will be described in detail in this chapter. The associated references are highly suggested for more extensive discussion on the development and use of the particular elements of the PSDD Framework.

The Production System Design and Deployment (PSDD) Framework, along with the PSDI Path, create an approach for translating the strategic manufacturing objectives into a real production system on the manufacturing floor. The entire PSDD Framework, including the PSDI Path, is based on the conceptual design process described in chapter 4. Therefore, the foundations of the Framework and its components are rooted in the scientific process of Axiomatic Design.

Using the axiomatic design paradigm in production system design is analogous to visualizing the design in several interrelated domains (see figure 3.1). The design hierarchy, which is a representation of the design across various *levels of scope*, is created by clearly defining the design objectives (function domain) and the corresponding design solutions (physical domain). The fact that the design is identified in terms of objectives and solutions, across all levels of the hierarchy is a critical factor in the success of the system implementation.

The approach to design and implementation in the PSDD Framework prevents "buzz-word" or "best-practice" mentality in organizational change. Several authors have shown that success in manufacturing system design and implementation can only arise from complete "systems-thinking;" all actions involved in the design and control, implementation and improvement of these complex systems must be made with the entire system in mind. Any design component or improvement initiative for manufacturing systems must be traceable to both (1) the functional objective it was mapped from and (2) the higher level functional objectives it was decomposed from. [Cochran, 1994] [Monden, 1983] [Black, 1991] [Shingo, 1989] [Senge, 1990].

To date, the main benefit of the PSDD Framework has been its use as a communication tool. Across all levels of an organization, the Framework provides the resources to understand the design objectives/solutions in terms of the higher-level goals. The Framework is intended to apply across product lines, industries and business functions.

The PSDD Framework is shown in Figure 5.1. The elements of the PSDD Framework include:

- Production System Design Decomposition
- FR-DP Examples (not shown in figure)
- Production System Design Matrix
- Production System Design Flowchart
- Production System Design System Evaluation Tool
- Production System Design Equipment Evaluation Tool
- Production System Deployment Steps

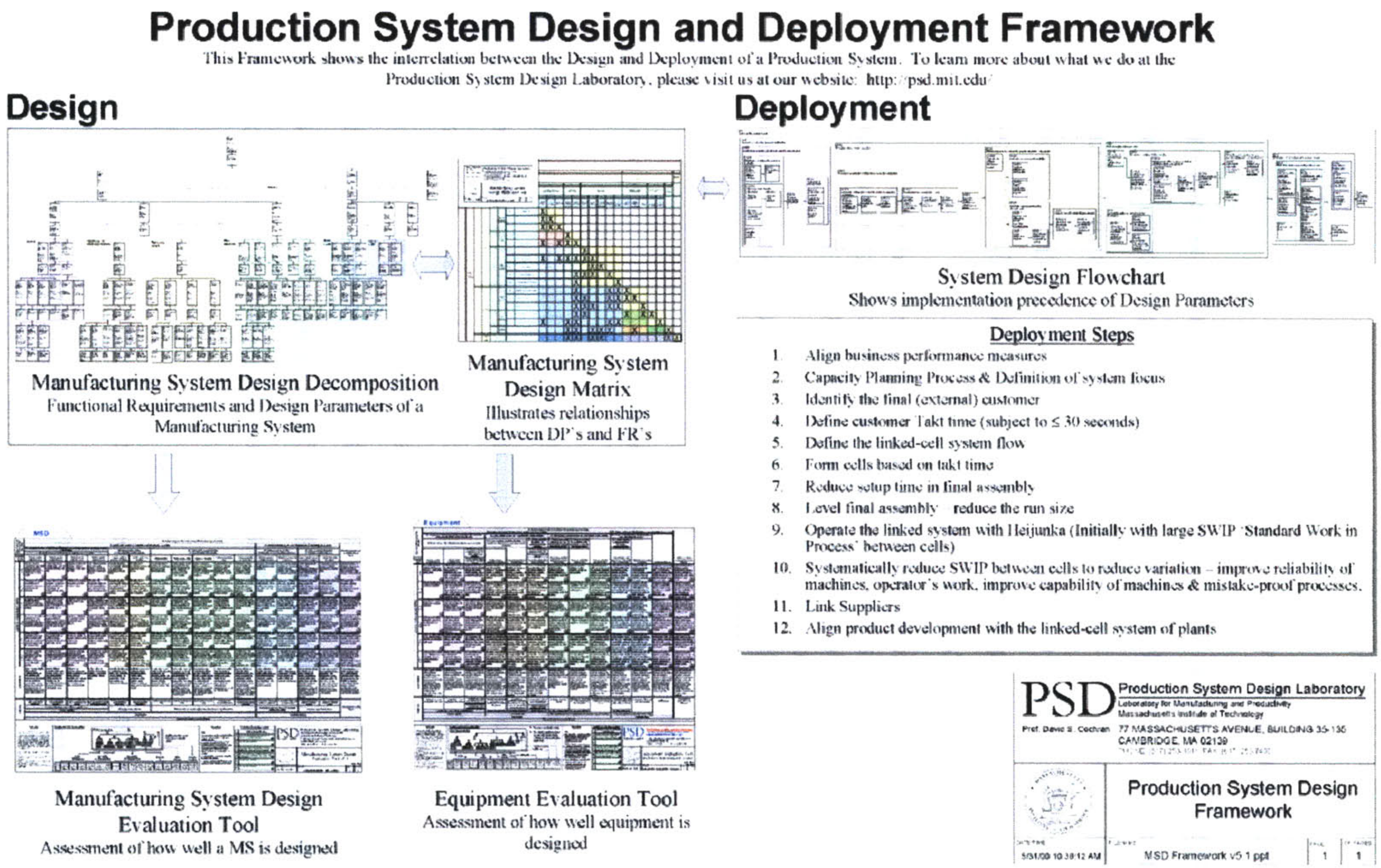


Figure 5.1
The Production System Design and Deployment Framework (version 5.1, 2000)

5.1 Design Decomposition

PSD DECOMPOSITION

During the PSDI Path, the Design Decomposition will serve as a map of the design hierarchy in the functional and physical domains. The relationship between high-level design objectives and low-level design solutions are clearly shown. During the design half of the PSDI Path, the decomposition guides the design by identifying the complete hierarchy of functional requirements to be met. Other benefits of the PSD Decomposition include [Cochran, 1999]:

1. Concretely describes a production system design concept
2. Adaptable to different product and manufacturing environments
3. Ability to create new system designs to meet new FRs
4. Applicable across industries
5. Indicates the impact of lower-level design decisions on total system performance
6. Provides the foundation for developing performance measures from a system-design perspective.
7. Connects machine design requirements to system objectives.

The decomposition begins by translating the customer domain of a manufacturing system design to the high-level functional requirement. As described in chapter 4, the customer domain of the manufacturing system design is defined by a set of internal and external customers. Internal customers include facets of the business such as owners, employees, and shareholders. External customers include the final users of the products being manufactured and any other group that is affected by the system design or performance. The Production System Design Decomposition begins with the functional domain defined as:

FR1 = Maximize long-term return on investment (ROI)

This single FR is the highest-level FR in the decomposition. Therefore, it completely defines the functional domain. The entire design hierarchy will be derived from this notion of the functional domain. When this functional requirement is mapped to the physical domain, a design parameter is chosen. As was described in the discussion of the axiomatic design process (chapter 3), the selection of design parameter is not unique.

There are several options here. It is the responsibility of the production system designer to ensure that the choice of DP is the best.

DP1 = Manufacturing System Design

This design parameter (DP1) is purposely vague. Several levels of decomposition must occur before implementation takes place. The design is therefore decomposed into the functional domain at the next level of the hierarchy (Level 2), creating a complete set of functional requirements:

FR11 = Maximize sales revenue
FR12 = Minimize manufacturing costs
FR13 = Minimize investment over production system lifecycle.

It can be seen that these 3 FRs, which define the design in the functional domain at the second level of the hierarchy, fully define the design objectives. If all of these functional requirements are achieved, the upper level functional requirement will also be achieved. As proof of this point, consider the equation for return on investment:

$$\text{ROI} = (\text{Sales} - \text{Cost}) / \text{Investment}$$

To map the design into the physical domain, design parameters to correspond to these functional requirements must be carefully chosen. The organization's approach to manufacturing strategy must be considered in these high-level design decisions because these decisions will dictate the structure of the design hierarchy at the lower levels. The following design parameters are chosen:

DP11 = Production to maximize customer satisfaction
DP12 = Elimination of non-value-adding sources of cost
DP13 = Investment based on long term strategy

When the design is decomposed to level 3, the following FRs and DPs are chosen. The design of the manufacturing system begins to take form at the subsystem level, and the functional objectives of the system can now be stated in more detail. Summarizing the FRs through the third level of decomposition, the objective of the manufacturing system can be stated as "Manufacture high-quality products, reliably on-time, at the lowest total cost with minimal investment."

FR111 = Manufacture products to target design specifications
DP111 = Production processes with minimal variation from the target

FR112 = Deliver products on time
DP112 = Throughput time variation reduction

FR 113 = Meet customer expected lead time
DP113 = Mean throughput time reduction

The complete PSD Decomposition is shown in appendix A. The mapping and decomposition between the functional and physical domain continues through six levels of the design hierarchy. The decomposition reaches a transition point at level 4. The higher-level objectives have been separated into branches, each of with deals with a particular aspect of the system. Functional areas area created, and the decomposition identifies the detailed requirements to be met. By viewing production systems in terms of the 7 branches, all of the system objectives are identified.

The 7 Branches of the PSD Decomposition

Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Direct Labor
Indirect Labor
Investment

In the quality branch, production is viewed in terms of the number of defects made. It is important to define what is meant by "defect" here, and a concise but complete definition is that a defect is a product that does not meet customer expectations. All the potential causes of defects are identified in the quality branch, along with the optimal solutions for preventing them. In essence, the quality branch provides a complete and fundamental method for achieving quality in the manufacturing system. The functional requirements and design parameters in the quality branch identify the objectives and solutions, respectively, required to achieve the higher-level system requirement of production without defects. The FRs and DPs have been decomposed so that the lower levels give detailed solutions that can be implemented.

In the Identifying and Resolving Problems Branch, the decomposition provides an approach for minimizing the time between the occurrence of a disruption in production and the elimination of the root cause of the problem. In this branch of the decomposition, the functional requirements define in detail the steps that must take place to solve problems at the source.

In the Predictable Output branch, the decomposition identifies four major sources of unpredictability in system operation. At the fifth level of decomposition, these classes are identified as disruptions in information, disruptions in equipment operation, disruptions in output from workers and material availability.

The Delay Reduction branch is significant in the design of flow in the manufacturing system. The functional requirements in this branch identify what must be done to create smooth flow of material through a plant. The five major types of delays are targeted in this branch: lot delay (inventory due to parts waiting for the rest of the transfer batch), process delay (inventory due to mismatch between production and takt time), run size delay (inventory due to lengthy run sizes & infrequent changeovers), transportation delay (inventory due to long transportation times), and systematic operational delays (interfering resources).

In the Direct Labor and Indirect Labor branches, the decomposition targets waste in labor operations. Waiting time and wasted motion in direct labor operation are eliminated in this branch, as well as ineffective indirect labor tasks.

FR/DP EXAMPLES

The FR/DP pairs in the design decomposition are implemented as physically integrated, functionally independent objects (structures) in the production system. The FR/DP examples in the PSDD Framework are intended to illustrate the design relationships defined by the FRs and DPs in the decomposition. Up and down the entire design hierarchy, the FR/DP pairs are physically manifested as integrated structures. The examples in the PSD Framework are intended to explain the physical significance of the abstract FR/DP terminology.

5.2 Interrelationships in the PSD

DESIGN MATRIX

During the development of the PSD Decomposition, functional requirements were mapped to design parameters across several levels of the design hierarchy. Each time a mapping from the functional to physical domain takes place, a design matrix is created. The design matrix defines the interrelationship between the design parameters and functional requirements. The composite view of the matrix shown in Appendix B illustrates the relationships between the Level IV DPs and FRs in the PSD Decomposition. In order to satisfy the independence axiom of the axiomatic design approach, the PSD Design Decomposition was developed such that the resulting Design Matrix is either uncoupled (diagonal matrix) or quasi-coupled (triangular matrix) at each level of the design hierarchy. The PSD Design Matrix shows that production system designs are highly path-dependent.

In most cases, the state of a particular design parameter of the production system will strongly influence the state of several functional requirements. This characteristic of production systems calls for a structured approach to implementation. Specifically, the PSD Design Matrix shows that certain functional requirements in the Production System Design Decomposition become prerequisites for others. The branches of the decomposition that are on the left-hand side of the diagram can be thought of as prerequisite to achieving the branches to the right. For example, a system that has successfully integrated the quality initiatives (DPs of the quality branch) into the design will have a greater probability of achieving all other system design objectives that are related by the design matrix.

Partial system design initiatives that integrate *dependent* FRs (as indicated by the design matrix) are prone to failure. By definition, these partial initiatives are not attainable without first integrating the prerequisite FR/DP pairs. Partial system initiatives are not *system designs*. For example, attempting to implement a Just-in-Time (JIT) system without achieving high quality, fast response time and predictable output is nothing more than an unfounded partial initiative. The PSDD Framework explains why these initiatives are impossible to implement successfully.

FLOWCHART

The PSD Flowchart provides a different way of visualizing the PSD Design Matrix. In the Flowchart, path-dependent design information is displayed as a sequence of design parameters. The core DPs of the design decomposition that are prerequisite to other FRs/DPs of the design are shown in the internal modules of the Flowchart. Assuming that the innermost DPs of the Flowchart have been integrated in the production system design, the outer DP modules are able to be successfully implemented.

5.3 System Performance

The performance of production systems is controlled by a series of state-based decisions, on both a short-term (real-time) and long-term (planning) time scale. The current state of a production system is sampled through the business performance measures, and the information is fed back and used to make control and operating decisions. Controlling a system based on a misaligned performance measurement system results in ineffective operation. In the implementation portion of the PSDI path, system performance measurement will define how the system is controlled and improved. Aligning the performance measurement system of the organization to the performance measures dictated by the system design must be done as part of the design process. As was seen in

Figure 4.3, the performance measures of the system are derived from the functional requirements, and can therefore be used to measure them.

Production systems are controlled with basic feedback control loops, as shown in Figure 5.2. In terms of this control architecture, the input to the production system is the control decisions and the output of the production system is a characterization of the achievement of the desired functionality of the system.

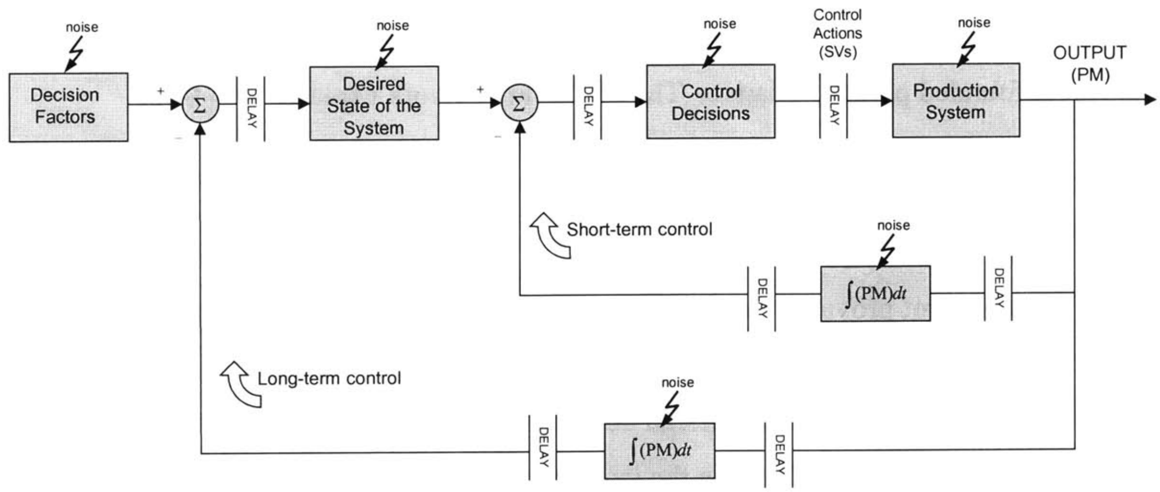


Figure 5.2
Architecture for the control of production systems

The *input* variables to the production system are defined in the process domain. In the control architecture, the inputs are the system variables (SVs) that can be manipulated by the controllers (managers, engineers, operators) of the system. The SVs of the system are manifest in the physical components of the system. As discussed in chapter 4, it is difficult to identify a complete set of SVs for a production system; the SVs are embodied in the design and operation of equipment, material and information flow links, direct and indirect labor operations and support resources. The actions of these human and mechanical elements will serve as the input to the production system in the control architecture. The control block in series with the production system defines the approach to manipulating the SVs that are input to the production system. Based on the signals from the feedback loops in the control architecture, control decisions are made and input to the production system as SVs.

An *output* variable can be thought of as the level of satisfaction of a function of the system. The functional requirements (FRs) of the system, identified in the design hierarchy (PSD Decomposition) define the complete set of system outputs. For example, as defined by the PSD Decomposition, the highest-level output variable in the control architecture is the ROI of the system. At lower levels in the design hierarchy, system functions include throughput time delays, operating costs and product quality. Each of these functions is a characteristic of the output of the system. The output signal of the production system is analogous to the state of the system in the functional domain, in terms of the system performance measures.

The functional domain is an abstract notion of the objectives of the system. To measure the degree to which the system meets its functional requirements, performance measures are used. Every functional requirement in the design hierarchy has an associated performance measurement variable. Performance measures (PMs) define the system quantitatively in the functional domain. The information in the feedback loops of the control architecture is in the form of the PM variables.

The short-term feedback loop in the control architecture represents the real-time control actions of the production system, for example, production scheduling information, material movement through the value stream and allocation of support resources such as maintenance. These short-term control actions are occurring continuously in the operation of production systems. The desired state of the system, which is determined in the long-term feedback loop, is compared to the current state of the system in terms of the performance measures. Based on the difference between the actual and desired states, control decisions are made and control actions are taken on the system.

The long-term feedback loop in the control architecture represents the strategic decisions that are made concerning the future of the system. Information on the long-term state of the system is fed back in the outer control loop in terms of *aggregated* performance measures (shown as an *integration over time* of the short-term PM data). Instead of using data hourly (as in the short-term control loop), the long-term feedback may occur on a weekly, monthly or even yearly basis. In order to determine the desired state of the system to be used in short-term control, this long-term performance information is compared against particular decision factors. Each production system will have a different decision factor scenario. An approach to identifying the important decision factors in identifying the desired state of the system was presented in Figure 2.1, the Focus Decision Matrix. Particular aspects of the processes, products, customers, market and industry of the production system will influence the choice of the desired state of the system.

The control architecture presented in Figure 5.2 is an abstract model of how decisions are made in production system design. As mentioned above, it is difficult to characterize the signals and control blocks of this model because many of the system functions (FRs) and input variables (SVs) are complex and physically integrated into the system components. This point reiterates the significance of the independence axiom of the axiomatic design methodology. As this control model shows, functional independence in the physical domain ([**DP**]) and the process domain ([**SV**]) will facilitate simpler control of the system toward the desired state. To summarize the significance of this control model, the following issues must be considered in the design of the production system:

1. *Delays*: Most connections in the control architecture are modeled with inherent delays. As information about controlling the system moves through the control architecture, it is delayed by the decision-making process. A characteristic of feedback control is that minimization and elimination of these delays will result in better system performance.

2. *Noise*: Each element in the control architecture is subject to noise. These disturbances come in many forms, and should be considered in the design of the production system and control elements. Examples of disturbances at the production system include machine shutdowns, unexpected quality issues and labor absenteeism.

Noise in the performance measurement block is analogous to missing or erroneous data. Designing the control blocks to be robust to noise will improve output performance.

3. *Transition of long-term goals to short-term goals*: Significant difficulty in the design process occurs when long-term goals must be translated to short-term goals. A complete definition of the functional requirements in the design hierarchy is critical to translating this part of the control architecture. The PSD Decomposition helps to identify how long-term, high-level objectives can be achieved by implementing short-term, low-level design solutions.

4. *Sensor design (What to measure)*: The control architecture shows the role that performance measurement plays in determining the control policy and therefore the output of the production system. Performance measurement systems that are not properly aligned with the desired functionality of the system will drive the system state away from the desired state.

5. *Controller design (What to do)*: Assuming that the performance measurement system is aligned with the functional requirements of the design hierarchy, proper control policy will drive the system state to the desired state. The relationship between the process domain (SVs) and the functional domain (FRs) should be understood in order to align the control decisions to achieve improved performance.

6. *Set point (Desired state)*: Long and short-term production system control provides the means for driving the state of the system toward the desired state, but the desired state of the system must be properly identified by the decision factors. This task is a main function of the high-level management of the organization and will typically rely on forecasts of the future of the decision factors (for example, customer demand, process technology, market size, etc.)

7. *Time scale of feedback and actions*: The control architecture makes a distinction between long and short-term control. The concept of the time-scale of control is being simplified in this model. In real-world control of production systems, there may be several time scales of control feedback, more than the two shown in the figure. Each feedback loop will rely on different types and amounts of PM data, and the longer-term control loops will typically rely on more historical data.

PERFORMANCE MEASURES (PM)

Every functional requirement (FR) in the PSD Decomposition has an associated performance measure (PM) that can be measured based on the current state of the system, used in the feedback control of the system. The PMs of the system will describe how well the FRs of the system design are being achieved at each level of the design hierarchy. In Appendix A, the performance measurement for each design FR is shown. Since the PMs of the design are solely derived from the functional requirements, the proper PM structure can be designed during the design decomposition process. To ensure proper control of the production system, the performance measurement system of the organization, from the plant management to the shop-floor operations must be aligned with the PMs of the production system design. Without proper alignment of business and PSD PMs, the production is at high risk of failure. [Cochran, Kim, Kim, 2000]

EVALUATION TOOLS

As the performance measures of the design (PMs) are intended to measure how well the functional requirements (FRs) are achieved, the evaluation tool is intended to quickly determine how well the design parameters (DPs) of the design have been implemented. The evaluation tool is an alternative way of measuring the performance of the system in terms of the physical domain, and may be useful in the long-term control decisions made in the system control architecture. In the PSD Framework, evaluation tools exist for the entire manufacturing system and for the equipment in the manufacturing system. [Chu, 2000] [Gomez, Dobbs, Cochran, 2000]. The evaluation tool describes the degree to which a real-world system has implemented the design parameters. A six-level scale is used, where a rating of 1 represents poor systems-thinking in implementation and a rating of 6 represents an ideal manifestation of a manufacturing system or equipment.

5.4 The PSDI Path

The components of the PSD Framework are resources that can be used during the several stages of the PSDI Path. As shown in Figure 4.4, the PSDI path is a progression from the high-level business objectives, downward towards a detailed system design and upward through a structured implementation procedure. The PSDI Path should not be viewed as a rigorous checklist that one can apply to production system design. Rather, it should be viewed as a map to guide the design and implementation efforts. The PSDI Path shows how the decision efforts at the lower levels are derived from upper-level decision and how the final system state is only achieved after several iterations of improvements in lower-level operations.

Prior work has been done on the development of "Steps to Lean Manufacturing." [Cochran, Milby, 1998] [Black, 1991]. The PSDI Path supports the notion of these steps, and a 12-step method to production system design is outlined here.

Early in the PSDI Path, production system designs begin as strategic initiatives. Manufacturing is a sub-function of the overall business structure, and therefore the manufacturing objectives are drawn from the objectives that are identified by the business. The upper-left most area of the PSDI Path is concerned with identifying manufacturing strategy from business strategy. Depending on several decision factors such as market, industry, process, product and customer attributes, the set of manufacturing strategic objectives are identified. Depending on these decision factors, the importance of cost, quality, flexibility, delivery performance and innovativeness is identified and used as the driver for the selection of high-level manufacturing system design alternatives.

The Decomposition in the PSD Framework provides a complete design hierarchy for production systems that is to be used in this early phase of the PSDI Path. Using the strategic objectives, the design hierarchy of production systems (PSD Decomposition) and the associated performance measures, key functional and physical areas of the manufacturing system can be identified that will play an important role in achieving the objectives. At this point, decomposition of the complete design hierarchy will identify the design approaches toward achieving each objective, and how each of the lower-level, implementable elements of the decomposition affect other system functions. Based on the previously identified high-level system strategic objectives, certain system functions in the design hierarchy may be more significant than others. Each manufacturing environment will be different in this respect. The important high-level system functional requirements identified here will drive the design through all lower-levels of scope.

1. *Alignment of performance measurement system.* Performance measurements plays a critical role in controlling production systems. In the PSDI path, the functional requirements, design parameters and performance measures for the entire design hierarchy are created during FR/DP decomposition. The performance measurement structure across all levels of the business must be aligned to the functional requirements in the design hierarchy to ensure proper decision-making during design, implementation and control of the production system. [Cochran, Kim, Kim, 2000]

2. *Identify elements of capacity & develop system focus.* In this step of the PSDI Path, the "type" of manufacturing system design is chosen. Based on the high-level objectives of the manufacturing system, a certain type of manufacturing system may be more appropriate, such as job-shop (batch production), "lean" cellular manufacturing, flexible manufacturing system or continuous flow (equipment paced). Part of the decision of system type is to develop the notion of capacity. As was discussed in section 2.3, several internal and external decision factors combine to determine what the focus of the manufacturing system should be. The idea of system focus (customer, process, product focus) is closely related to the notion of capacity in the system. Depending on the focus decision, the system will be comprised of

"chucks" of capacity aligned towards producing a group of products with similar characteristics. For example, a single production value stream capacity element may be dedicated for a particular customer, customer group (market) or product family. The manufacturing strategic objectives, developed early in the PSDI path, will guide this decision process. The strategic role of cost, investment, quality, long and short-term flexibility and responsiveness in the manufacturing system will affect the capacity planning decision. This strategic decision will define the system type to an extent; small increments of capacity can be added in cellular manufacturing whereas the capacity of transfer line systems can only be increased in large chunks. Cellular manufacturing systems with a flexible view of capacity tend to have fewer lost sales and lower operating costs than dedicated line systems. Cells that have separated the worker from the machine are capable of operating over a wider range of production volumes than dedicated lines that require a fixed number of workers regardless of production rate. [Cain, Cochran, 1995].

Figure 5.3 shows two different types of capacity plans for manufacturing systems. In this manufacturing system example, the value streams are focused on customer demand volume. Therefore, capacity increments must be added to compensate for increasing customer demand volume. The example shown in (a) might represent a transfer line system. Capacity can only be added in large increments as demand increases, by adding an entire transfer line to balance the increase in demand. In (b), the system is more flexible because capacity can be added and removed in small chunks. Cells that have separated the worker from the machine have flexible capacity as shown here. When the takt time changes, these flexible cells can change the production volume rapidly and in small increments by re-balancing the workloops in the cell.

In addition to the size of the capacity chucks in the system, some other factors will be significant in defining capacity and focus for the system. For example, the *cost* of the capacity increments, the *lead time* for implementing changes in capacity and whether or not the changes in capacity will lead or follow changes in demand for capacity may need to be considered at this point in the PSDI path.

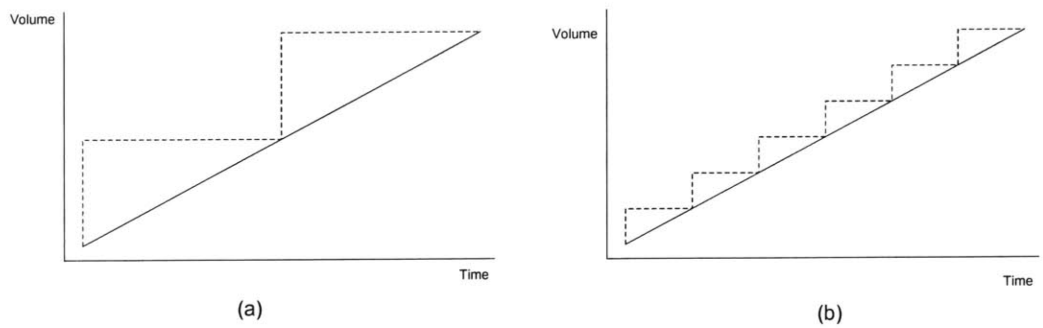


Figure 5.3
Capacity plans for two types of manufacturing systems.

3. *Identify External Customer (Groups).* Once the focus and capacity decisions are made in step 2 above, the customers of the system can be defined and customer groups may be formed. The external customers are the users of the product at the end of the value stream, and depending on the system boundaries defined, the external customers might be users, distributors or downstream manufacturers. As part of this step, important customer attributes must be identified. Particularly important external customer characteristics include: expected quality characteristics, expected lead time, target cost and variation in demand.

4. *Determine takt time.* Once the capacity elements and focus are defined, external customer groups are formed and pertinent information about the customer is gathered, the takt time of each value stream in the system may be calculated. At this point, it is necessary to define the term *takt time.* The takt time, analogous to the heartbeat of the system [Cochran, 2000] is the unit of time on which one part must be produced by the system in order to satisfy customer demand. If on the average, the production system is not producing to takt time, then the customer demand is not being met.

To calculate the takt time of a production system, the amount of available production time during a given time interval (one week, perhaps) is divided by the average customer demand during that time interval. For example, if a plant operates two 8-hour shifts, 5 days per week, with 1 hour of breaks per shift, the *total* production time is 70 hours/week. If this plant's operating efficiency is 85% (accounting for unplanned inefficiencies such as downtime, scrap, labor slowdowns, etc.) then the *available* production time is 59.5 hours/week. During any given week, the customer(s) might order a different number of parts. The average customer demand is used to calculate the takt time. If the customer(s) order on the average 3500 parts/week, then the takt time is equal to (59.5 hours/week)(3600 sec/hr)/(3500 parts/week) = 61.2 seconds/part.

If the average customer demand is difficult to determine because of large variation in demand volume, then the system must be designed to accommodate volume flexibility. For systems with manual labor content, takt times less than 30 seconds should be avoided. Fast takt times lead to labor operations that are isolated and tied to the automatic cycle of the machine. Labor flexibility is difficult to achieve in systems with fast takt times.

5. *Define the flow of the linked-cell system.* At this point in the PSDI Path, all of the necessary information has been gathered to design the material and information flow in the value stream at the linked-cell level of scope. Based on the definition of capacity and the takt time, the physical material flow and information flow paths between system elements (processing and storage) can be designed. This procedure will be discussed in detail in chapter 7. For each element and link of the value stream, a set of standard procedures must be developed as part of this step to control the flow of material and information through the system.

6. *Form Cells based on takt time.* The information from steps 1-5 define the system at the high levels of scope. The remainder of the design half of the PSDI Path is the

design of the detailed subsystems (elements: SWIP inventory, cells, equipment, labor operations & links: material and information flow). Physically integrating all of these elements and linking structures on the manufacturing floor is the beginning of the implementation path.

7. *Setup reduction.* At the lowest level of scope in the PSDI Path, the details of every component of the system are designed. Based on all of the higher-level decision, equipment, cells, work methods, and flow paths are designed *for the system*. These integrated structures are then implemented on the manufacturing floor and operation of the elements of the system begins. Improvements to the system that will take place later on in the PSDI Path rely on effective design of the lower-level subsystems, and a critical part of the design is to reduce setup time. Quick changeovers will allow the system to achieve level production, being more responsive to the customer demand mix.

8. *Level and pace production at the pacemaker process (e.g., final assembly).* This part of the PSDI Path deals with the propagation of information through the system to initiate production and material flow. Production only occurs when authorized by an information signal. Therefore, the state of production is controlled by pacing the release of information to the manufacturing system. There are some advantages that arise if information is released to the system in small discrete, pre-defined increments. The smallest convenient amount of production information that can be delivered to the system is called the *pitch*. The pitch is equal to the takt time multiplied by the container size. The container size is the number of parts that are transported together in a single batch. In a system with a takt time of 60 seconds and a container size of 5, the pitch is 300 seconds. If information is issued to the system in small discrete time intervals, production control has more flexibility in accommodating for variation or unexpected schedule changes. Also, if information is delivered in small batches, the act of delivering information can also serve as a status check on current production. If information is delivered every pitch interval, but parts are not available to be

withdrawn, this condition indicates that something is wrong in the manufacturing system.

During every demand interval, the customer(s) will request a mix of part types. For example, a customer might request a quantity of 400 of part type A, 400 of type B and 200 of type C. Assuming that the cycle times to produce these 3 part types are equivalent, then the takt time is calculated based on a customer demand of 1000 parts. Production is *leveled* if the system produces the proper mix of part types every customer demand interval. If production is not leveled, then more inventory is required to meet customer demand and the system's throughput time and response time is unnecessarily long. In chapter 6, it will be seen how leveling occurs in the flow of information with the use of leveling elements (e.g., leveling and pacing box, a.k.a. heijunka). The leveling and pacing box is a tool that is used to visually manage the production information that will be released to the upstream system each pitch interval. An example of a leveling and pacing box is shown in Figure 5.4. Information on the mix and volume of customer demand is used to fill the box. Each row represents one part type and each column represents one pitch interval. A card in the box represents a signal to produce one container of the corresponding part type at the appropriate time.

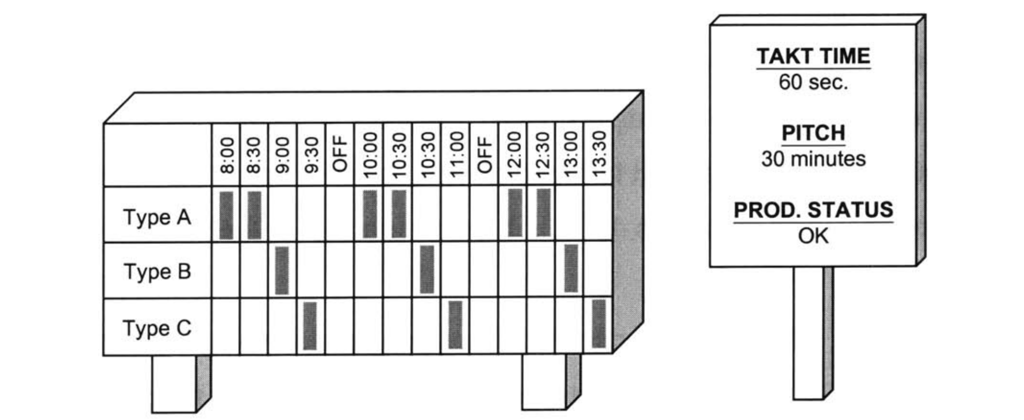


Figure 5.4
Leveling and pacing box in the shipping/scheduling department with production information

9. *Operate linked cell system with large SWIP.* At the early stages of the implementation part of the PSDI Path, when efforts are directed at the system elements at the low levels of scope (equipment, operations, cells) the system may require large amounts of inventory to compensate for unexpected variation, in order to provide predictable output to the customer. During the implementation path, inventory can be used to evaluate and track improvements in the system. As elements become more reliable and delays are eliminated, inventory can be reduced. A more risky improvement strategy is to reduce inventory to force improvements in the system.

10. *Improve Predictability and reduce SWIP.* The reduction of inventory and improvement in predictability in system elements are events that are very closely related. Improvements in the operation of single system elements translate to entire system improvements because buffers can be reduced and continuous flow can be established, reducing delays throughout the material flow path. In the Toyota Production System, an analogy has been made to "reducing the water level to expose the rocks." [Monden, 1993] As the standard inventory is reduced (water level decreases), the variation in the system is exposed, such as machine downtime or quality problems (exposing the rocks) The system elements must respond with improved reliability. Inventory can be used as leverage to improve; reducing inventory places stress on the system to improve. However, there is inherent risk to removing SWIP without having dedicated resources for improving system reliability. Without a structured approach to improvement, the elimination of buffers will result in missed customer shipments due to inherent variation and unpredictability.

11. *Link suppliers.* Once the implementation has progressed enough so that the system reaches a high level of predictability, suppliers can be linked to the production system with material and information links. Receiving high-quality, on-time, reliable shipments from the supplier will cascade improvements downstream. The suppliers will be expected to provide reliable output, assuming that the internal production system is issuing consistent and reliable demand information.

12. *Integrate product development.* The manufacturing system should be a critical part of the product design effort, in order to reduce waste in the overall product life-cycle. If the product designers understand the objectives of the manufacturing system design hierarchy and the approaches taken to accomplish the objectives, in terms of the detailed design of the workstations, conflicting characteristics between the production system design and the product design can be resolved.

These 12 steps summarize the PSDI Path. The discussion here is intended to apply to the general case of production system design, so more distinction may be required to apply the PSDI Path or the 12 Steps to a specific case.

Modeling is used throughout the entire PSDI path to serve as a common "language" of the system representation. The system design is visualized in terms of the modeling environment. During both the design and the implementation portions of the PSDI Path, the modeling environment will be used as a tool for analysis, design verification communication. In chapter 6, a modeling environment to perform these functions along the entire PSDI Path is proposed.

6 The Analytical Model of Production Systems

Production systems can be characterized by complex interactions between machines, materials, information and people. In order to truly understand what occurs in a production system, one must have a detailed understanding of the disciplines of engineering, logistics, team dynamics and strategic management. As with all modeling efforts, it is impossible to truly represent or predict the impact of an input or disturbance on a complex manufacturing system, but we can use modeling to better understand the basic behaviors of the system. Visualizing the production system and its flows is a critical part of understanding a system. In order to implement a production system, a model must be communicated to the people involved.

The following list summarizes the functional uses of a production system model and simulation environment:

1. Visualization of system connectivity
2. Discrete event analysis for design and control
3. Communication of design solutions in a dynamic representation (especially useful during implementation)

In axiomatic design terminology, the three statements above are the customer wants [**CW**] of a modeling/simulation environment. Loosely translating these statements to the functional requirements [**FR**] of the modeling/simulation environment:

FR1. Configurable/updateable architecture: the environment can be changed easily.

FR2. Robust analytical simulation ability: the environment can be used to analyze systems effectively, in many ways.

FR3. Consistent modeling approach/capability across all system levels of scope: the environment can be used to model a complete system with low detail or a part of a system in high detail.

FR4. Real-world design decision categories (production system DPs) map to decision categories in modeling environment: the variables in the model directly map to the variables in the manufacturing system.

In order to create a useful manufacturing system modeling environment, two important characteristics of production systems must be considered. Reiterating from chapter 2, these characteristics are flow and level of scope. The modeling approach must comply with these characteristics of production systems.

First, there are two types of flow in a manufacturing system: (1) material flows from suppliers, through value-adding processes to the customers, and (2) information, whether it be a schedule or a production signal, generally flows opposite to material, from customers toward suppliers.

The second important characteristic is that a production system is a nested group of objects. A production system can be viewed as a hierarchy of low-level objects (manufacturing processes, workstations, material containers) that combine to form groups of objects (cells, assembly lines, departments), which also combine to form large systems (plants, value streams, supply chains).

Several methods for modeling production systems have been developed and implemented as software packages or design approaches. Some of these products may be well suited for particular applications of production system design modeling/simulation, but in most cases, these products have limitations in terms of meeting the functional requirements of production system modeling/simulation environments. Value stream mapping [Rother, Shook] is an example of a formal approach to production system modeling. Witness®, Simul8® and DENEB Quest® are examples of software packages designed for specific applications of production system design modeling.

As a caveat, the reader should note that the modeling concept and application presented here has been developed as a tool to apply to general production system modeling situations. Before the ideas presented in this section are applied to a specific manufacturing system, they must be refined and tailored to a particular case.

6.1 Object-Oriented Modeling (OOM)

If an object-oriented modeling approach is used to create a model of production systems, the criteria discussed above can be met. OOM is beneficial for this use because it models the *physical* objects of the system, as opposed to the functions performed by the system. This characteristic of the modeling environment will help to satisfy modeling environment FR1 (configurability) and FR4 (mapping of design decisions). This characteristic also makes the OOM approach general-purpose, and can therefore be used to model the flows in a production system, at all levels of scope. [Mize, Bhuskute, Pratt, Kamath, 1992], satisfying FR3 (mixed-level modeling capability). Functional independence between the components of the model is maintained, and the components can be grouped to form components at a higher level in the system hierarchy. OOM can aide in the design, control *and* implementation of production systems. Other approaches to modeling and simulation fall short of these benefits.

Mize, et. al. discuss other benefits of using an OOM paradigm in manufacturing system design, such as its compatibility with simulation software architecture, high flexibility, and low cost to develop. These characteristics of OOM modeling environments are aligned with FR1 (configurability) and FR2 (analytic robustness).

The basic idea in OOM is that all components of the model are treated as *objects*. An object is a model of a system component; a system component may be physical (parts, machines, inventories) or abstract (information, control logic, time clock), but is always modeled as an object. All of the objects in the model are classified based on a hierarchy, i.e., an object can be a subgroup of another object. An object that is decomposed into more specific objects is known as a *class*. In other words, a class is an object that classifies a group of objects based on common characteristics. For example, a model may contain an object class known as "machine." If further differentiation is necessary between machine objects, other objects can be defined such as "lathe," "mill," "drill press" and "broach." Each of these objects exists in the "machine" object class.

An object has a set of *attributes*, similar to variables, which describe the object. For example, the attributes of a "machine" object may be "cycle time," "current status," "standard work-in-process (SWIP)" and "scrap rate." Attribute values may change over time and differ between instances of an object, but all objects in the same class can be defined by the same set of attributes.

6.2 Modeling Production Systems

In this section, the OOM approach will be used to create an approach to modeling production systems. Every production system has different characteristics and every instance that a model is used for a different purpose. It is because of these complexities that one should view this modeling approach as a general-purpose starting point. The modeling scheme presented here is appropriate for visualizing production systems and can be applied at all levels of scope.

Value stream mapping is a tool proposed by Rother and Shook in the text, Learning to See [Rother, Shook, 1998]. Value stream mapping is used to visualize the flow of material and information flow in production systems. The mapping tool can be applied in situations where existing systems are being modeled, or in the case where a new system is being designed. For consistency, the icons used in developing the OOM model in this chapter are similar to the icons presented by Rother and Shook.

Figure 6.1 shows the classification of the most basic "primitive" object classes in a production system. These primitives are like building-blocks that will be combined to form models of real-world system components. The icons that will be used to represent these modeling objects are show at the bottom of the figure.

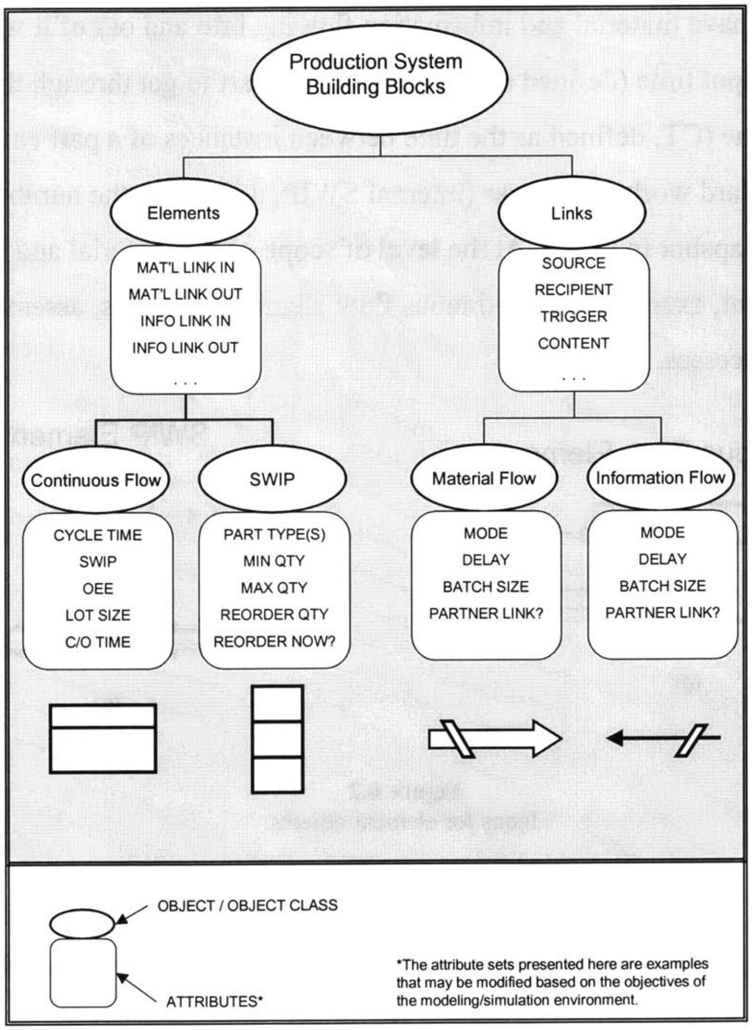


Figure 6.1
Structure of an object-oriented production system modeling/simulation environment

ELEMENTS

Generally, *elements* will be used to model the *physical* components of the system. In this object class, there are two types of elements: *continuous flow* and *SWIP*.

CONTINUOUS FLOW ELEMENTS

A continuous flow element is one in which the material and/or information moving through the element can be modeled as a pipeline type of flow. A diagram of a continuous flow element is shown in Figure 6.2(a). In the general case, a continuous flow element will have material and information flowing into and out of it with an associated throughput time (defined as the time for one part to get through the entire element), cycle time (CT, defined as the time between instances of a part exiting the element) and standard work-in-process (internal SWIP, defined as the number of parts in the element at a snapshot in time). At the level of scope of the material and information flow through a plant, examples of continuous flow elements are cells, assembly lines, and manufacturing processes.

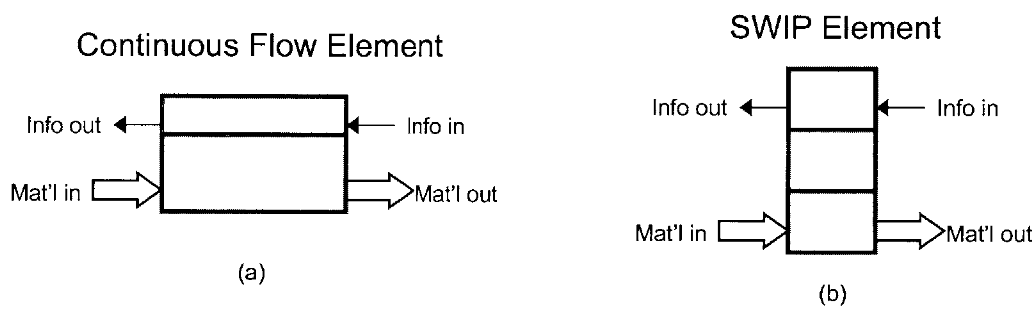


Figure 6.2
Icons for element objects

A basic characteristic of continuous flow elements during steady state operation is:

$$(\mathrm{CT})(\mathrm{Internal\ SWIP}) = \mathrm{Throughput\ Time}$$

A physical component of the system can be modeled as a continuous flow element if over every small interval of time during operation, the quantity and sequence of material and information entering and exiting is preserved. The key word in this criteria statement is "small." Depending on the modeling application and the level of scope of the model, it may or may not be acceptable to model a part of the system as continuous flow. For example, in modeling production systems at the level of cell design, it is acceptable to represent the manufacturing processes in the cell as linked continuous flow elements. If, however, the system is being modeled at the level of scope of the linked-cell system, it is unnecessary to model every individual process in each cell. Rather, an entire cell can be modeled as a continuous flow element with the same attributes as an individual manufacturing process: cycle time, internal SWIP, throughput time, uptime reliability, scrap rate, etc.

SWIP ELEMENTS

A standard work-in-process (SWIP) element is used to model those physical entities in a system in which quantities of material or information can build up. The flow through SWIP elements is not continuous; the quantity and sequence of parts and information in and out of the SWIP element is *not* preserved. A graphical representation of a SWIP element is shown in Figure 6.2(b). In general, a SWIP element will have different attributes based on its control logic. A managed SWIP "marketplace", for example, will have a designated min and max quantity for each part type. SWIP is used in a production system to decouple material flow. Sometimes, SWIP elements are called buffers.

LINKS

To complete this basic set of modeling components, a second object class called *links* will be defined. A link represents a path of movement through a system. For the scope of this research, we will consider the movement of material (parts) and information (orders, signals, production authorization) between elemental objects.[2] Material and information moves through the system, via dedicated material flow links and information

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[2] One of the features of this modeling environment is the capability to expand the scope of the model to include any component of real-world production systems. The most basic set of objects are defined here, as seen in Figure 6.1. It is also possible to create other objects within the two element and link object classes to model other types of production system components. In the context of the design, implementation and control of complete production systems, one may see fit to expand this model to include an object class called "resources." Within this object class, limited capacity system resources such as direct and indirect labor, maintenance personnel, general-purpose material handling equipment and tools/fixtures can be modeled. These resources can flow between element objects via dedicated resource links. Depending on the level of scope of the model application, this level of detail may be helpful. For the scope of this research, however, these elements have been omitted, since the focus is on *material* and *information* flow.

flow links, respectively. Figure 6.3(a) and 6.3(b) show graphical representations of material and information flow links, respectively.

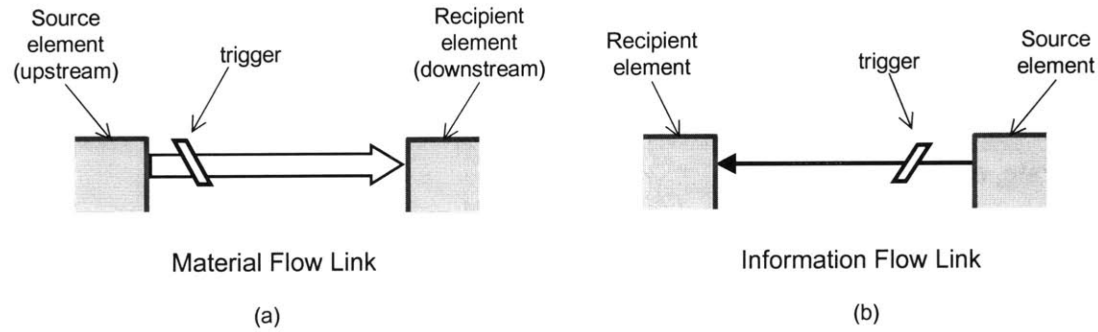


Figure 6.3
Icons for link objects

A link will connect two element objects at its associated node. For example, a material flow link connecting the material output node of a SWIP element to the material input node of a continuous flow element may be used to represent the movement of parts from a raw materials marketplace to the material supply racks of an assembly cell. Also, an information flow link connecting the information output node of a SWIP element to the information input node of a continuous flow element may be used to model the delivery of a production order to replenish a marketplace from its supplier fabrication cell.

LINK OBJECT ATTRIBUTES

Both material flow links and information flow links will have a common set of attributes (each model instance of a link object will have a distinct value for the following variables):

1. *Source element*: Which element object in the model will the material or information flow FROM? Any element with the appropriate output node is a possible value for this attribute.

2. *Recipient element*: Which element in the model will the material or information be delivered TO? Any element with the appropriate input node is a possible value for this attribute.

3. *Trigger*: What event will initiate the release of material or information from the source element? A trigger is a control parameter of the link. Different manufacturing system designs will exhibit different values for this attribute. Examples include: constant time interval and variable quantity, constant quantity and variable time interval, real-time signal (visual or otherwise). [Monden, 1993]

4. *Content*: What package of material or information will be delivered across the link? Values for this attribute will depend on the conditions of other objects in the system. These values can be thought of as being dependent on other values. The content of a piece of information flowing through the system will depend on the state of an element, the content of a material link, or the content of another link in the system. For example, the content of material moved out of a marketplace will depend on the content of a piece of information arriving at that marketplace, which in turn depends the content of a partner material link further downstream in the system. In a properly designed manufacturing system, the content of any link in the system will depend on the content of one or more other links in the system. The exception to this rule is a link that is connected to an external element, such as a customer. The content of the information flowing from the customer into the system is independent of the current state of the system; it is modeled as an input to the system. However, the content of these inputs may be reliable enough to predict.

5. *Mode*: What are the characteristic properties of the method of transporting the material or information? This attribute can be subdivided into several attributes depending on a case-by-case basis. Examples of sub-attributes and possible values are shown in Figure 6.1.

6.3 Integrated Structures

In the discussion on axiomatic design, the notion of physical integration with functional independence was presented. Most real-world manufacturing system components are manifestations of several integrated design parameters. As long as the several functions remain independent, it is often desirable to combine several physical pieces into one implementable chunk, in order to make the design simpler. Machines, cells, information systems and support resources are all examples of physically integrated, functionally independent components. Modeling these integrated structures is feasible with the OOM approach.

By combining the building blocks created in section 6.2, integrated structures in the manufacturing system can be modeled as single objects. The four primitive object classes defined above (continuous flow element, SWIP element, material flow link, information flow link) will be used to create new objects. These new objects will then be used to model the production system at the linked-cell system scope.

MACHINES

Although it is often considered to be one of the most basic manufacturing system components, a machine is actually a complex integrated structure made up of all four of the primitive modeling objects. No two machine designs are the same, but in general, a machine designed for manufacturing systems will consist of a load routine, process routine (milling or turning, for example) and unload routine. Each of these routines can be automatic or manual, and will have an associated cycle time. Machines that are designed for single piece flow (to minimize lot delay) hold one part in the process routine at any point in time (SWIP = 1 part). This general description of a machine designed for manufacturing systems can be modeled as shown in Figure 6.4(a). The model consists of a continuous flow element, representing the process routine, linked to a SWIP element representing the unload routine. The material flow into the machine, through the processing routine and the unload routine, and out of the machine. Each material flow link is triggered by a partner information flow link. In this case, the information content is simply a signal to trigger material flow. No additional information content is necessary.

Combining this structure into a single modeling object, a machine can also be represented as a continuous flow element as shown in Figure 6.4(b). This model of a machine is more appropriate for modeling efforts at a higher level of scope than the equipment design level. During linked-cell system design, for example, modeling the specific routines of a machine is unnecessary; one continuous flow element may be sufficient.

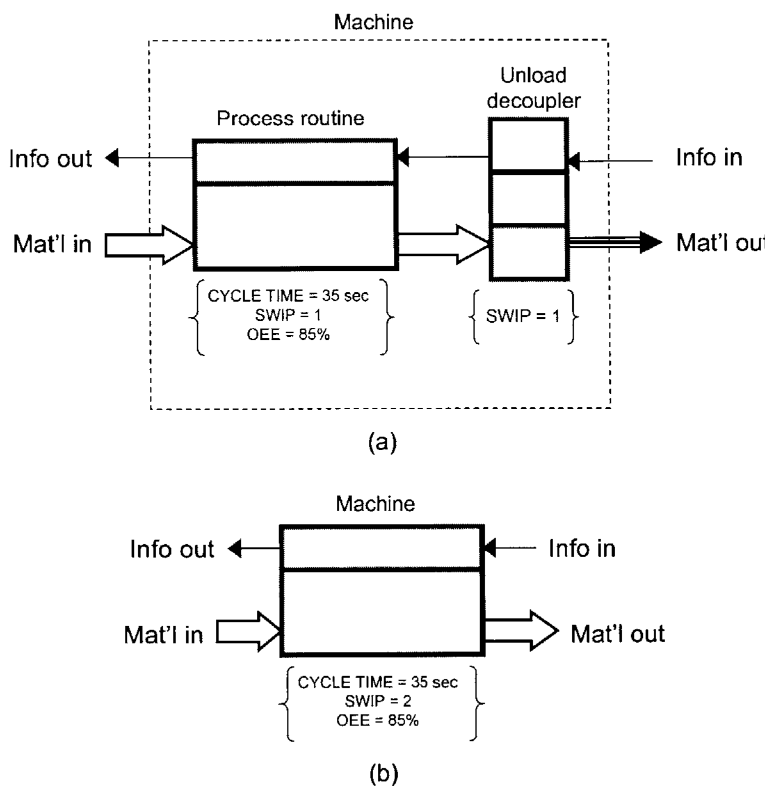


Figure 6.4
Equivalent representations of machines at different levels of detail

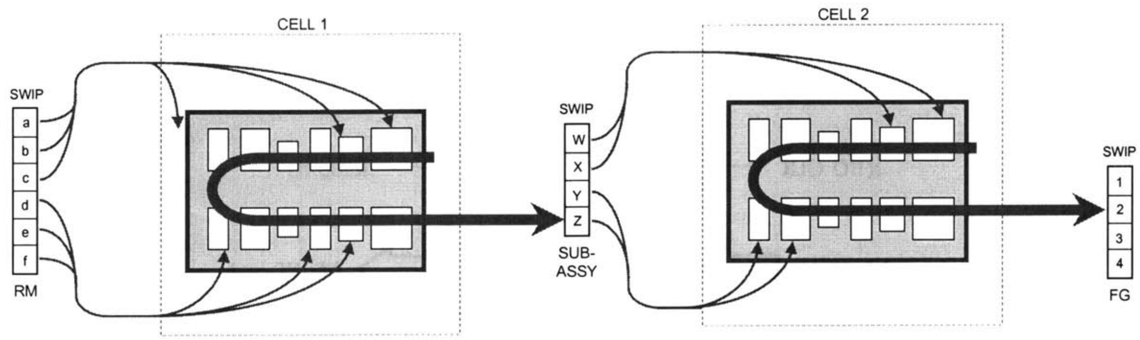
CELLS

A cell is an example of an integrated structure at level of scope above the machine level. Several machine and SWIP objects can be combined with link objects to form a cell model. To create the cell model, consider the physical structure of a cell. Figure 6.5(a) shows the physical movement of material through a cell. Material is transferred from the supply buffer (raw materials) to the input racks at the workstations. By processing the part, these raw materials are converted to form a finished product that flows out of the cell toward the customer. If the entire cell is considered as a single modeling object, the material flow can be represented as shown in Figure 6.5(b). These two diagrams are representing the exact same flow of material; 6.5(a) is a more detailed model than 6.5(b).

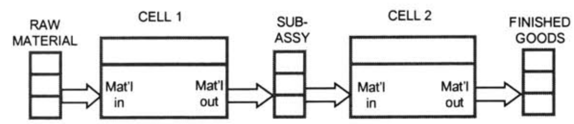
Next, to complete the model of a cell, consider the flow of information through a cell. Figure 6.6(a) is a diagram of how production-order kanban (POK) and withdrawal kanban (WLK) are used in a manufacturing cell. The POK flows from the downstream (customer) element to the cell in order to signal the quantity and type of parts to be produced by the cell. POK are moved along with the finished product of the cell. Conversely, WLK flow from the cell upstream toward the supply element to signal delivery of needed raw material. The WLK then travel downstream with the raw material to the point of use. The representation in Figure 6.6(b) is equivalent to the physical diagram, at a higher level of scope. The entire cell is modeled as a single element, with POK information flowing in and WK information flowing out. These two information streams are related by the consumption rate of parts in the cell.

If the models of 6.5(b) and 6.6(b) are combined, it is evident that a cell can be modeled as a single continuous flow element with four link connections and attributes such as cycle time, overall effectiveness and SWIP. Figure 6.7 shows the object model of a cell. By moving up in level of scope, the detail of the physical integration of material and information flow through the cell is simplified. This simplification may be desirable for certain types of modeling efforts, but in order to properly communicate the complete system design, this type of model is insufficient.

> In order to communicate a system design effectively, it must be modeled at all levels of scope (i.e., levels of detail). Key design information may be lost if simplified models are used to represent integrated structures.

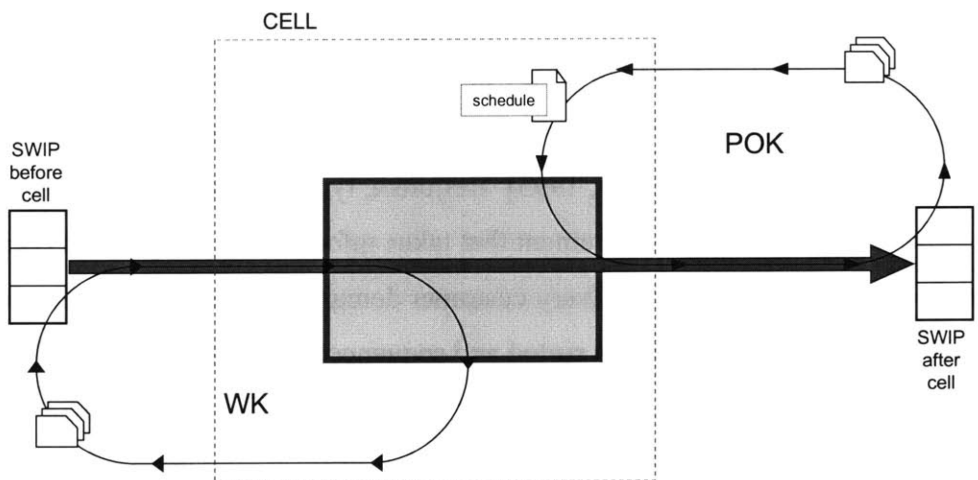


(a)

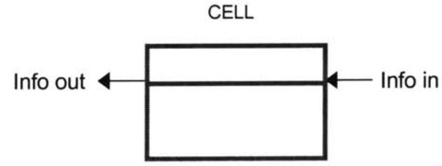


(b)

Figure 6.5
Partial model of a cell showing material flow in a detailed view (a) and simplified view (b)



(a)



(b)

Figure 6.6
Partial model of a cell showing information flow in detailed view (a) and simplified view (b)

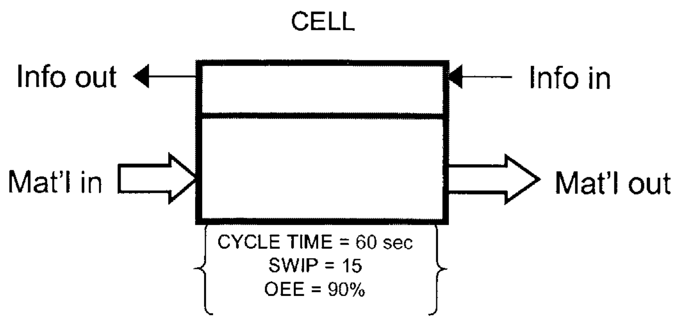


Figure 6.7
Model of a cell object to be used at the linked-cell system level of scope

INFORMATION LEVELING AND PACING (HEIJUNKA)

To reduce process delay and run size delay in the system (see section 5.4 step 7), information may be leveled by volume and mix. Heijunka is a method used in TPS to achieve level production. [Monden, 1993] Heijunka, typically internal to the scheduling department in a plant, is a system element that takes information as input and issues sequenced information as output. Every customer demand interval, information is received by the heijunka and can be sorted and sequenced to create a level production schedule. Every pitch interval, information may be released from the heijunka to the production system.

The function of leveling information flow in a production system (for example, by the use of heijunka) can be modeled as an element with an information input link and an information output link. The frequency of information signals input to the leveling element is the customer demand interval. For example, if the scheduling department receives customer orders every Monday morning, then the customer demand interval is one week. The frequency of information output from the leveling element is the *production control interval*. The minimum value for the production control interval is the pitch. Figure 6.8 shows the model of an information leveling element.

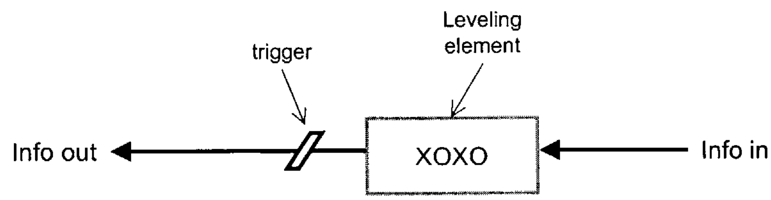


Figure 6.8
Model of an information leveling element. Heijunka is an example of an information leveling element.

SHIPPING & SCHEDULING

Functional departments in the plant, such as shipping, scheduling, purchasing, can also be modeled with this approach. Typically, no processing of material takes place in these functions, but material and information flow through them nonetheless. The operating characteristics of each functional department will vary between different production system designs. Examples of an integrated shipping/scheduling department are shown here, for a build-to-stock system and a build-to-order system. For repetitive manufacturing systems, the "build-to" characteristic refers to the way final customers are linked to the rest of the value stream. In chapter 7, the build-to characteristic will be discussed further. It will be shown that certain systems require a particular "build-to" strategy, depending on certain physical parameters of the system (e.g., customer expected lead time and system response time).

BUILD-TO-STOCK

In a build-to-stock system, the final element in the path of material flow before the customer is a buffer. Shipments to the customer are pulled from this final buffer, typically referred to as a *finished goods inventory*. When a customer order is received, the corresponding parts are shipped from the finished goods inventory. The scheduling department will then issue production authorization to a predetermined place in the value stream, based on the status of the finished goods inventory and other scheduling policies.

In TPS, leveling is an important scheduling policy that is used to reduce waste in the upstream system. Releasing a predictable, level schedule is a fundamental prerequisite for eliminating lot delay in the Toyota Production System. If production were not leveled, extra inventory would be required to deliver the correct mix of parts to the customer. This extra inventory would create delays, lengthening the throughput time of parts through the system. Level production systems conduct more frequent changeovers to reduce SWIP in the system, for reduced delay in throughput time. Therefore, setup time reduction becomes an important prerequisite to level production.

The model of a build-to-stock shipping department is shown in Figure 6.9. The finished goods inventory can be modeled as a SWIP element. Incoming information (customer orders) trigger outgoing material flow. The information flow propagates through the leveling element upstream to the rest of the production system. Release of information from the leveling element is typically triggered by either:

1. *Constant Time Interval.* At fixed time intervals, packages of information are issued upstream. [Monden, 1993]

—OR—

2. *Constant Quantity (SWIP element attributes).* When a predetermined quantity of parts remain in the SWIP location, an information signal is issued immediately, authorizing production of that part. This control policy has been called "constant-quantity, non-constant time." [Monden, 1993].

A specific point to be noted here is that different manufacturing system designs may require different control policies for production authorization triggering. The logic behind the control policy in terms of production authorization triggering should be rethought for each specific design case. Production control resources in the plant such as material handlers, forklifts and dunnage will be allocated based on the triggering policy that is chosen. In most cases, if the production volume through a part of the system is relatively stable, it will be more logistically feasible for the material and information to be handled at constant time intervals (trigger policy #1). However, in cases where part types are used quite infrequently or unpredictably, it may be more efficient to convey material and information in constant quantities (trigger policy #2).

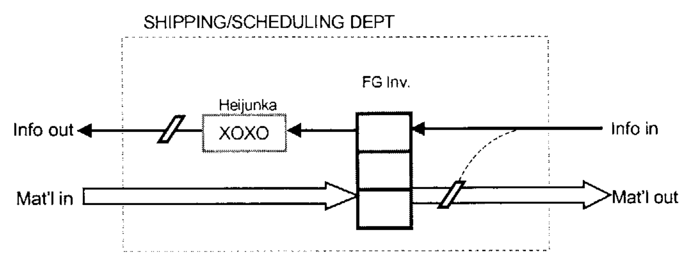


Figure 6.9
Model of shipping/scheduling department for a build-to-stock production system

BUILD-TO-ORDER

In a build-to-order system, there is no standard finished goods inventory. After the final processing step in the value stream, parts are queued and shipped directly to the customer. Orders are received from the customers, processed by the scheduling department, and conveyed as production authorization to a point in the value stream. The model of a shipping/scheduling department for a build-to-order system is shown in Figure 6.10. Within the shipping/scheduling department, the information may be leveled. From the leveling element, information release may be triggered by either of the two control policies described above.

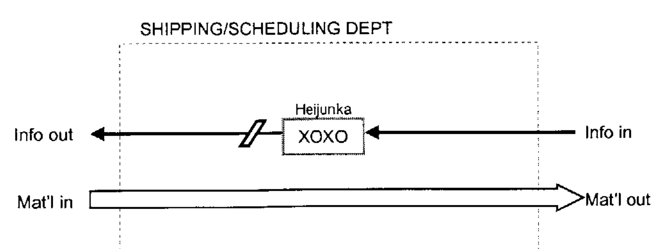


Figure 6.10
Model of a shipping/scheduling department for a build-to-order production system

6.4 System Mapping Technique

The objects and object classes created in this chapter can be used to model a complete production system. The modeling environment developed here was intended to be functional at any level of scope; it can be used to simulate detailed work operations or entire value streams. In this section, this modeling environment will be used to map the production system at the level of scope of a linked-cell system. The linked-cell system is viewed as material flowing through continuous flow elements (cells) and SWIP elements (inventory) on its way from suppliers to customers. The other half of the linked-cell system is the information flowing through the system elements, opposite the material flow. Figure 6.11 shows a model of a type of production system. Customer orders trigger delivery from the finished goods inventory. Production authorization information is leveled in the shipping department and flows upstream when it is triggered by a time signal. The assembly cell receives information from the heijunka in the shipping department and sends material requirements information to the WIP inventory. The assembly cell sends these withdrawal signals in constant time intervals, and when this information arrives at the WIP inventory, material replenishment to the assembly cell is triggered. When a predetermined quantity of parts is reached in the WIP inventory, a production authorization signal is triggered and sent to the fabrication cell. This production authorization and withdrawal loop repeats upstream, as the fabrication cell pulls from the purchasing department (raw material inventory) and the purchasing department orders from suppliers.

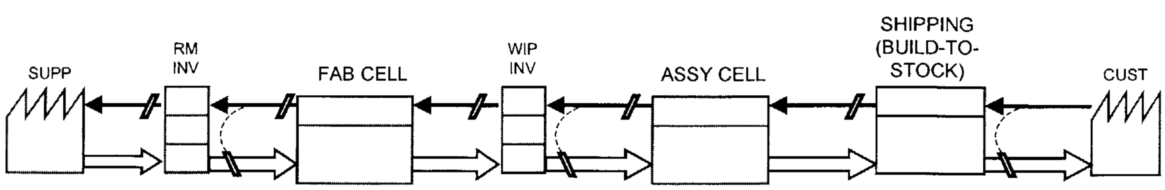


Figure 6.11
Value Stream Model of a production system at the linked-cell level of scope

MODELING EXISTING SYSTEMS (BROWNFIELD)

A good technique for creating a model of an existing system is to follow the flow of material either from customers upstream or suppliers downstream. Throughout the system map, note all potential material flow links and measure necessary element/link attribute data. Relevant data may include process cycle times, element cycle times, delays, batch sizes (move quantities), change-over times, buffer sizes and queue lengths, and process reliability (uptime) to use as attribute values for the modeling objects.

To complete the map, the information flow must me modeled as well. To see information flow through the system, "follow" the customer order through administration and across the manufacturing floor. Keep track of administration times, leveling elements and delays. Take note of the triggers and content sources for the information links and the control policies behind them. These link attributes may be very subtle in the real system. In some cases, there might not be a standard procedure for triggering the link or defining the content. A sign of a good system design is one in which the control policies such as triggering and content definition are standard control policies of the system.

6.5 Designing New (Greenfield) Systems With Modeling

Modeling systems as they are being designed provides valuable support to the design and operation functions. A static representation of the flow of material and information through the manufacturing system may help communicate the design solutions, but a dynamic simulation of the *movement* of material and information through the model system will accurately represent the intricacies of the system design, in particular, the work methods of the direct and indirect labor operators. The modeling approach in this chapter is a sufficient method for visualizing systems for simulation. The production system, which is a complex flow system on several levels of scope, must be communicated in its entirety to be implemented.

The PSDI Path was introduced in Figure 4.4. This tool will be revisited in chapter 7 and its application to the design and implementation of material and information flow in the production system design will be expanded upon. During each step of the PSDI path, the modeling approach presented in this chapter will provide essential support. The designers will benefit from the modeling approach's analytical capabilities and the managers/operators will benefit from the modeling approach's communicability and flexibility.

A final note to be mentioned about the modeling approach presented in this chapter is that it should be viewed solely as a foundation for modeling/simulation applications. The objects and attribute variables discussed here form a paradigm through which the production system can be viewed at several levels of scope at once. The functional requirements of such a modeling/simulation environment were listed at the beginning of this chapter, and the basic modeling objects created here should support these functions. If the modeling/simulation environment presented here were to be applied to a real production system design case, the objects and attributes should be strictly defined. Also, this modeling/simulation environment can be manifested in several different ways. For example, depending on the needs of the designer (creative design, analysis, communication), any of the following can utilize this modeling approach: a static drawing (value stream map [Rother, Shook, 1998]), a computer analytical simulation, computer visual animation, or a physical simulation model in which people can interact with the model to visualize the work methods involved in the operation of the system.

7 Designing Linked-Cell Manufacturing Systems

This chapter will focus on a portion of the PSDI Path presented earlier, specifically the steps taken toward step 5, defining the system flow at the value stream level. Certain design decisions are made during this phase of the PSDI Path, based on the higher-level objectives that were identified and decisions that were made. Using the terminology developed in chapter 6, the system will be modeled at the linked-cell level of scope as a structure of linked elements. Cells and departments are modeled as continuous flow elements that have a cycle time and standard WIP. These elements are isolated with SWIP inventories and linked via material and information flow.

The linked-cell manufacturing system is an integrated structure in the manufacturing system. It is subject to the functional requirements and design parameters that are defined in creating the design hierarchy. In the following sections, the PSD Decomposition will be used to identify critical functional requirements pertaining to the design of the linked-cell system, along with the corresponding design parameters and performance measures for control. From there, a sequence of design decisions will be discussed, along with design guidelines where applicable.

7.1 Design Requirements

The PSD Decomposition, which was discussed in section 5.1, is shown in its entirety in the appendix. The decomposition creates the design hierarchy in the functional and physical domains, linking the highest-level design objectives to the lowest-level solutions through mapping and decomposition.

The linked-cell manufacturing system is a particular type of integrated structure in the overall production system. Subsystems of the linked-cell system include cells, inventories, material flow links, information flow links and functional departments.

Certain FR/DP pairs in the PSD Decomposition have particular significance during the design of the linked-cell structure. Figure 7.1 is a diagram showing the elements in the design decomposition hierarchy that apply at the linked-cell level of scope. The boxes that are shaded represent an important relationship. In other words, the functional requirements that are shaded represent a subset of the overall functional domain that pertains to the design of the manufacturing system at the linked-cell level of scope. Table 7.1 summarizes the design decisions involved in defining the production system flow at the linked-cell level of scope. For each design decision, the appropriate functional requirement and design parameter pairs are identified, along with guidelines for the design decision. Each of these decisions is described in detail in section 7.2.

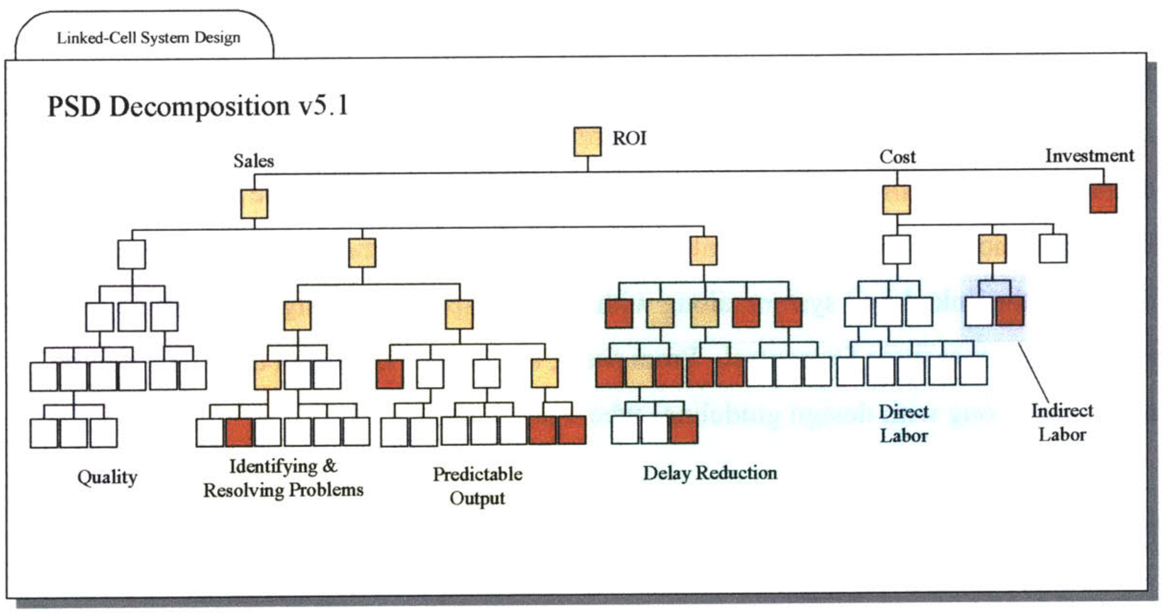


Figure 7.1
Subset of the PSD Decomposition with significance in linked-cell system design

Table 7.1
Design decisions for determining the flow at the linked-cell level of scope, along with appropriate FRs, DPs and design guidelines.

PSDI Step	Design Decision (SV)	Design Function (FR)	Design Approach (diagonal DP)	Guidelines
2	Capacity & Focus	13		1. Chose the system type based on the high-level system objectives
		Minimize investment over production system lifecycle	Investment over system lifecycle	
3 & 4	Takt time	T21		1. Takt time = (available time) / (average demand) 2. Proper selection of OEE allowance
		Define takt times	Definition or grouping of customers to achieve takt time within an ideal range	
5.1	Batch Size	T1		1. Design subsystems for SPF
		Reduce lot delay	Reduction of transfer batch size (single-piece flow)	
	Lot Size	T3		1. Design subsystems for quick changeover 2. Information leveling to achieve EPE demand interval
		Reduce run size delay	Level production (Production of the desired mix and quantity during each demand interval)	
5.2	Decouplers	T23		1. System Response time < Customer expected lead time 2. "Build-to-???" decision (order or stock)
		Ensure that part arrival rate is equal to service rate	Arrival of parts at downstream operation according to pitch	
5.3	PA Point	12		PA point as far upstream such that flow is continuous downstream from the pacemaker process
		Eliminate information disruptions	Seamless information flow	
5.4	SWIP Levels & Replenishment	P14		1. Levels of SWIP inventory based on response time and reliability 2. Integrate standardized replenishment tasks in subsystem design
		Ensure material availibility	Standard material replenishment system	
5.5	Links/Loops	R112		1. Standardize all of the attributes of the material and information flow links: source, recipient, trigger, mode, content
		Identify disruptions where they occur	Simplified material flow paths	
		P11		
		Ensure availibility of relavent production information	Capable and reliable information system	
		T23		
		Ensure that part arrival rate is equal to service rate	Arrival of parts at downstream operations according to pitch	
		T5		
		Reduce systemic operational delays	Subsystem design to avoid production interruptions	
		12		
		Eliminate information disruptions	Seamless information flow (visual factory)	

7.2 Linked-Cell System Design Procedure

CAPACITY PLANNING AND FOCUS

The linked-cell system will begin to take form during the definition of focus and capacity planning stage of the PSDI Path. Different definitions of focus will lead to different structures of the material and information flow in the linked-cell system. Figure 7.2 shows flow diagrams for 3 types of focused manufacturing systems.

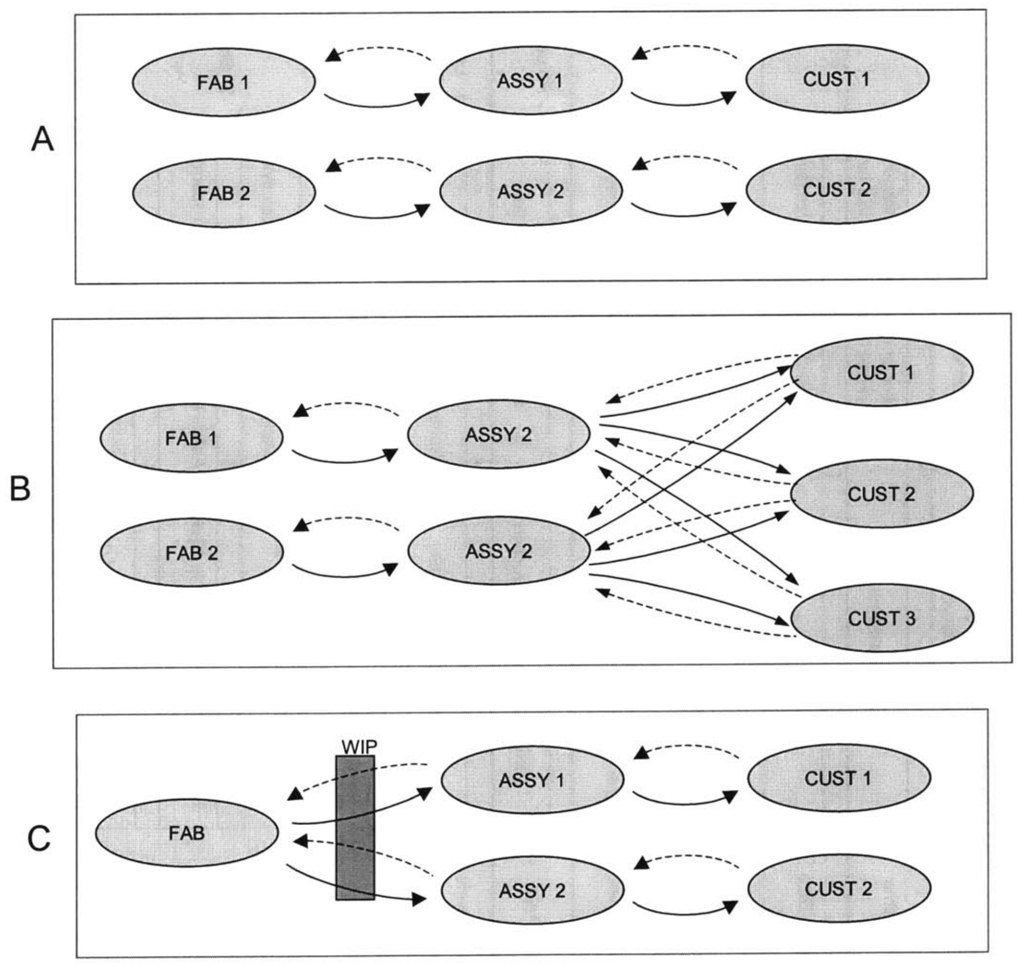


Figure 7.2
Three examples of flow in focused manufacturing systems
(a) Customer focused (b) Product type focused (c) Process focused

System (a) is a customer-focused system. Each flow path is dedicated to the demand of a single customer plant. This type of system is ideal for customer responsiveness.

Production at the upstream elements can be synchronized to the customer demand mix and quantity.

System (b) is a product-focused system. Each flow path in the plant is dedicated to a particular product or product family. Products flow from each final assembly cell to each customer. This flow pattern is more complex that system (a), and some of the benefits of customer responsiveness may be sacrificed. However, this system will exhibit less changeover cost during operation and will be more flexible to innovation for products with short life-cycles.

System (c) contains a capital-intensive "monument" process. In this example, the fabrication cell is not dedicated to any product line or customer. All products originate at the same fabrication cell. This system design will require more inventory to compensate for downstream demand variation, and will therefore have longer throughput times. This system design may be necessary in cases where investment or process constraints dictate single equipment purchases.

TAKT TIME CALCULATION

Once the focus decision has been made, each flow stream has an identified set of customers. In example (a) above, there is a single customer for each stream. The takt time can be calculated for each element in the path. In the case where a value stream has several customers, demand information can be aggregated. The formula for calculating takt time was given in chapter 5. To reiterate, the takt time is the customer demand cycle time. A part must be produced every takt time interval to meet customer demand.

Allowances for lost production time must be built into the takt time, including element OEE, changeover time, and maintenance. If the total production time in a shift is divided by the customer demand for the shift, the result is a *pure* takt time, but this number assumes that production never ceases during the shift.

Any production system can have its own strategy for what to account for in takt time. Some standard allowances include lunch breaks, coffee breaks, scheduled maintenance, team meetings and scheduled changeovers. However, unexpected allowances should also be accounted for. The decision that is to be made here is a tradeoff. The production managers must decide how much inefficiency to build into the takt time calculation.

The *effective* takt time compensates for production inefficiency. If too much production inefficiency is allowed for, investment will increase because there is more waste allowed for in the system. Cycle times must be faster and more inventory might be required as safety buffer. On the other hand, if not enough inefficiency allowance is built into the takt time, the system will not be able to meet demand without improvements. Investment will be reduced, but more operating costs are sacrificed to meet the low standards for OEE. Maintenance, quality and changeover times become critical factors in operating costs. If the system is not able to improve in these areas, it is risky to plan with such low inefficiency allowances.

Another issue in this tradeoff is improvement. A key concept in successful manufacturing systems implementation is continuous improvement. To sustain growth and change, complex systems must have leverage for improvement. [Senge, 1990] If a lot of inefficiency is built into the takt time, the system will have excess capacity and therefore improvement will not be critical to system performance. In this case, management must create a long-term plan on implementing improvement with dedicated resources.

DESIGN OF SYSTEM FLOW IN 5 STEPS

1 BATCH SIZE AND LOT SIZE

In Table 7.1, FR-T1 identifies the design objective to reduce lot delay. If batch sizes are too large, significant delay will occur because of parts waiting on other parts before being transferred to the next process. By designing single-piece-flow (SPF) into the material flow links, lot delay can be eliminated. SPF is especially important at the level of scope of equipment and cell design to ensure smooth flow through the continuous flow element. Otherwise, delays will be long and responsiveness will decrease. For the linked-cell system, parts should be conveyed between cells in batches small enough so that the pitch of the system is at a reasonable level (pitch = container size x takt time). If the pitch interval is very long because of large batch sizes, flexibility in controlling production will be lost. However, the container size should not be too small to require frequent material transfers over long distances in the plant. The batch size can be decreased if DP-T4, "Material flow oriented layout" is implemented, thus allowing for a smaller (more powerful) production control interval.

A set of functional requirements identified in Table 7.1 are FR-T31 and FR-T32. Together, these objectives dictate that the system should minimize run size delay by leveling production. As was described in section 6.3, information is leveled by mix in the production system such that the mix of parts *produced* is equivalent to the mix of parts *demanded* during the customer demand interval. A characteristic of a production element to describe how frequent changeovers occur is the EPE variable. EPE, which stands for "every part every" is followed by a time interval to indicate how level the system is. An optimal target for EPE is EPE customer demand interval. If this criteria is maintained, no additional inventory in the system will be required to deliver the exact customer order on time. DP-31, "Information flow from downstream customer" will be implemented via the information links that connect system elements. This design parameter indicates that part of the information content that is delivered upstream must include the proper mix of parts demand each interval. DP-T32, "Quick changeover for material handling and equipment" applies across all levels of scope in the design hierarchy. For the linked-cell system design, specialized material handling equipment for different part types must be able to be changed-over rapidly to decrease the burden of frequent changeovers associated with level production. In section 6.3, it was shown that heijunka is a tool to be used to level the information flow through the system. [Monden, 1993]

2 LOCATION OF SWIP (DECOUPLED FLOW)

Wherever possible, processing functions should be combined into continuous flow elements in the plant to eliminate delays in throughput. Even if processes must be separated into distinct continuous flow elements or cells because of some constraints on the layout of the plant, the flow between them should remain continuous (FIFO), only being decoupled when necessary.

If the throughput time of material flowing through a cell is sufficiently long so that the downstream customer will be waiting for parts, it is necessary to place a SWIP element after the slow cell. The guideline to follow when placing SWIP elements in the material flow is identified by the following rule:

$$\text{Upstream Manufacturing response time} \leq \text{Downstream expected response time}$$

Where response time is defined as the total time between the placement and receipt of a production order. The response time is the sum of the administrative and delivery lead times. If the order is issued to a production element (cell), then the delivery lead time will include the production lead time through the cell. If, however, the order is issued to a SWIP element (storage), the part is waiting in the buffer and can be withdrawn immediately. Flow must be decoupled with SWIP in order to satisfy this design rule, and placing SWIP between cells will eliminate waiting for the downstream cell because of long response times of the upstream cell.

This guideline applies in determining the "build-to" characteristic of the system described in section 6.3. The manufacturing response time, defined as the time between the receipt of a customer order signal and the delivery of the order can be shortened by placing a finished-goods-inventory at the end of the value stream. Systems with short throughput times as compared to the customer shipping interval should be designed with a "build-to-order" flow strategy, whereas systems with long throughput times should be designed with a "build-to-stock" flow strategy. Refer to Figures 6.9 and 6.10 for models of these types of flow paths.

Besides isolating lead time problems, decouplers can be used to isolate cycle time mismatches and TEMPORARY reliability problems, while sacrificing throughput time and quality feedback. Inventory should never be used as a permanent buffer against time or quality unpredictability.

3 FIRST PRODUCTION AUTHORIZATION (PA) POINT

Once the SWIP elements have been placed in the system, production can be paced by setting the production authorization (PA) point. A single seamless value stream flow should have only one PA point to avoid complications arising from independent scheduling of production. The pace and mix of production in the entire system will be set by the single production authorization point. Production authorization information will exit the scheduling element and travel upstream to the pacemaker process. [Rother, Shook, 1998] Information will then cascade upstream from the pacemaker process in the form of withdrawal for SWIP elements or production authorization signals for processing elements. An ideal system design will have the first production authorization point (pacemaker process) as far up-stream in the system such that all elements downstream of the pacemaker are continuous flow. All material flow downstream of the pacemaker process must be continuous (without buffers).

4 SWIP LEVELS AND REPLENISHMENT ROUTINES

The levels of inventory in each SWIP element should be controlled with standardized operating policies. The standard may vary over time based on the reliability of the material flow from the upstream element or the information flow from the downstream element, but at any point in time the level should be strictly controlled. During the implementation of the production system, the levels of SWIP will be reduced as the reliability and delays of system elements is reduced.

The two attributes that are common to all SWIP buffers are desired min level and desired max level. During production, the level of inventory in the SWIP should vary between the min and max level. In the event of unexpected production problems upstream, the inventory level may drop below the min level.

Depending on the trigger mechanism used to issue information signals upstream, the SWIP element may have a third attribute called re-order quantity (ROQ). In the case of constant-quantity variable-time replenishment, the re-order quantity is used to trigger outgoing information signals. Whenever the quantity of parts removed from the SWIP reaches the ROQ, an information signal is triggered. In this type of replenishment scheme, the following guidelines are used to set the inventory levels:

The material replenishment routine must be designed concurrently with the cells and the information system. [Mierzejewska, 2000]

Zero inventory is not necessarily the goal of system operation. Rather, inventory is used as a countermeasure (temporary solution) to balance the effects of:

- Unpredictable downtime or yield (safety stock)
- Setup time
- Volatile mix and volume of demand (buffer stock)

The SWIP should be viewed as a tool in the system that can be used to (a) monitor and signal production in the short-term and (b) monitor system progress in the long-term by controlling the standard levels using the guidelines in Table 7.2. [Monden, 1993]

MIN = amount of safety stock	This inventory in the SWIP will be used to Compensate for (a) instability in downstream orders, (b) instability in upstream time output, (c) scrap rate of upstream parts and (d) reliability of the material flow links in and out of the SWIP.
DEL = amount of stock to cover upstream response time	This inventory in the SWIP will be consumed by the downstream (customer) element during the response time of the upstream (supply) element. It is a function of the re-order quantity.
ROQ = quantity of parts withdrawn before triggering information release	There are many possible values for ROQ, but it cannot be smaller than the batch size. Smaller values of ROQ correspond to more rapid information transfer upstream.
MAX = MIN + DEL + ROQ	The total size of the SWIP element is the sum of the inventory amounts listed above. When parts are removed from the SWIP, a (kanban) signal is activated. When the trigger is reached (either by time or ROQ) all active (kanban) signals are issued to the upstream element in the form of production authorization. At any time, the number of active (kanban) signals and parts in the SWIP is constant and equal to MAX.

Table 7.2
Attributes of SWIP elements

5 ESTABLISHING LINKS/LOOPS

To this point in the design path, all of the element objects of the linked-cell system should have been designed based on the original capacity and focus decisions. The remaining objects to design are the material and information flow links. Every link in the linked-cell system should have a partner link of the other type, traveling in the opposite direction. The two types of flow join together to form material and information loops linking the elements of the linked-cell system.

As described in chapter 6, each link has a set of attributes that must be identified as part of the manufacturing system design. Recall that the attributes of link elements are: source element, recipient element, trigger, content and mode. The detailed design of material and information flow is analogous to defining each of these attributes for every link in the system. Once the attributes have been defined for each link, the design must be implemented and communicated at the level of the manufacturing floor. Just as standard work operations exist for processing and direct labor operations, standard work methods must exist for the operation of the material and information links in the system.

8 Application of the PSDI Path

8.1 Initial State

The PSDI Path is an approach that can be taken to create production systems that accomplish the manufacturing objectives. Complete system design projects are complex problems that require rigorous design and repetitive improvements during implementation. Following the PSDI Path enables the system designers to cascade the objectives throughout the design and enable a rapid and successful implementation program.

The PSDI Path view of system design projects was used to guide a production system design project for Visteon Automotive Systems Chassis Division, a tier-1 automotive components supplier for Ford Motor Company. The project took place in a stamping plant that manufactures, among other products, catalytic converters for passenger vehicles. The 1.5 million square foot plant has approximately 2000 employees and services about 55 regular customer plants and distributors.

Traditionally, the plant operated with a batch-and-queue production system, where customer order forecasts are funneled through a central production control department and schedules are delivered to each process in the value stream. Large variable amounts of inventory are scattered throughout the system to buffer against mismatched operating patterns and unreliable time output at the processes. Figure 8.1 shows a traditional value stream for manufacturing catalytic converters in this plant. The icons presented in chapter 6 to represent system objects are used to model the production system at the value stream level of detail. Line arrows show information transfer and block arrows show material transfer between system elements (blocks). In this system, material and information flow links are not triggered by standard control policies. Rather, flow in this system occurs haphazardly, whenever parts and schedules are available. Material and information flow do not appear in pairs. Because of the way this system was designed, throughput times are unnecessarily long and unpredictable. In order to improve the system with respect to these objectives, the complete system must be redesigned, including (1) value streams designed for material and information flow, (2) cells and SWIP elements to support improvement and (3) machines and fixtures designed for time and quality reliability.

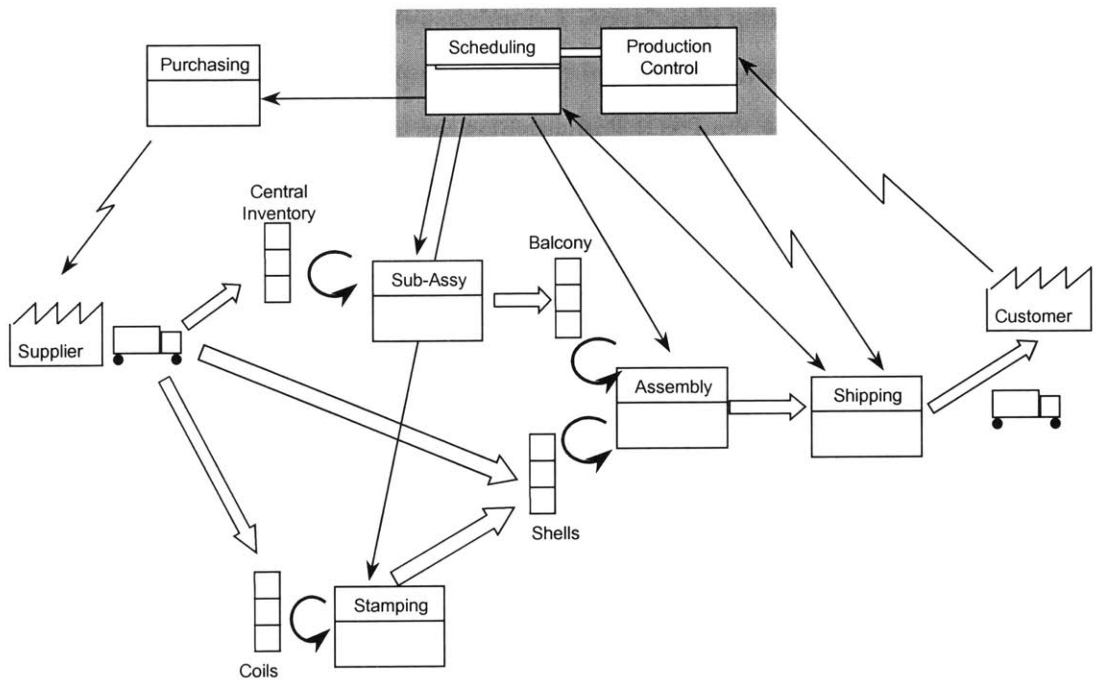


Figure 8.1
Traditional batch-and-queue value stream in the plant

STEP 1: ALIGN BUSINESS PERFORMANCE MEASURES

To begin this project, the strategic manufacturing objectives were identified: improved customer satisfaction through better product quality, more reliable output and quicker delivery of orders at reduced cost. At first glance, these objectives seem impossible to achieve simultaneously because of the nature of the tradeoffs between quality, reliability, delivery lead-time and cost. Of course, if the traditional system design were tweaked in attempt to achieve these objectives simultaneously, the efforts would fail, resulting in the expected tradeoff with cost. Therefore, following the PSDI Path toward a complete system redesign is necessary.

By defining the project goals in this way, the initial steps of the PSDI Path are underway. The manufacturing objectives have been identified and by using the design hierarchy shown in the PSD Decomposition, the important system functions and design approaches are identified. The management information system can be aligned to the performance measures directly from the design hierarchy FRs. Once the PM system is aligned, a program for gathering data and *visually* displaying progress throughout the plant is implemented. All employees from the plant manager to the operators will know the critical performance measures during production.

8.2 Linked-Cell System Design

STEP 2: DEFINE FOCUS AND CAPACITY

The redesign of the system begins by identifying the important characteristics that will determine the focus and capacity elements of the system. The catalytic converter is a bulky product with awkward geometry. Depending on the model, a finished catalytic converter assembly may weigh approximately 35 pounds. Production lead times are very short compared to the customer demand interval of 4 days. Yearly product volumes of high-runner parts are on the order of 250 – 500 thousand parts. Because of the complicated geometry of the product, dedicated machines and fixtures are required for assembly processes. Finished goods and raw materials are quite large, so inventory space fills up quickly. Data on the history of customer orders shows that the monthly average demand remains relatively stable, varying no more than ±10%. Figure 8.2 shows 3 types of catalytic converter product families. The components and configurations used to assemble the parts in a single family vary slightly, but common material handling and processing equipment is used. Within each product family, fixture changes are sometimes (but not always) required to switch to different end item part types.

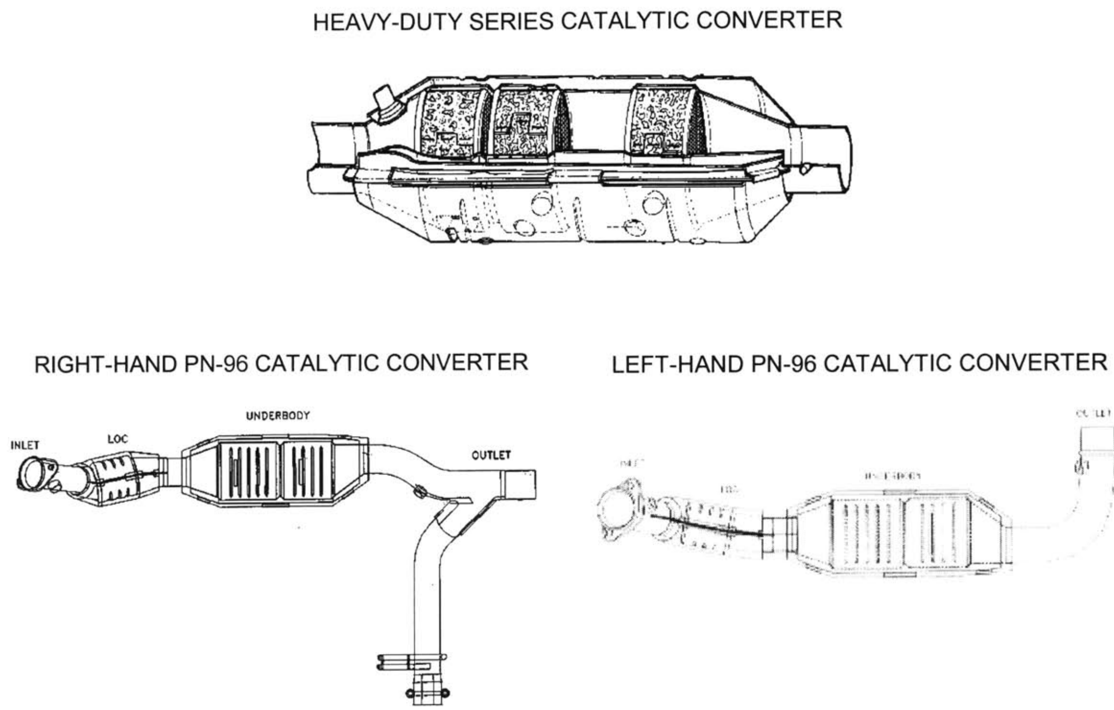


Figure 8.2
Three part families of catalytic converters manufactured at the Visteon plant

These characteristics of catalytic converters and assembly processes call for a system with value streams dedicated for product families. One catalytic converter part type may be used by 3 or 4 customers, so having customer dedicated lines would require infeasible investments in several pieces of right-sized machines, fixtures and material handling equipment and frequent time-consuming changeovers. In order to simultaneously reduce cost and improve output quality, reliability and leadtime, value stream elements (processes, inventory) will be designed as lean cellular elements linked with material and information flow. Other system type alternatives such as transfer lines, batch-and-queue systems, continuous flow systems and high-speed assembly lines are not capable of meeting all of the manufacturing objectives simultaneously in this product environment. The new system design will be made up of value streams focused for product groups with similar equipment requirements, as shown in Figure 8.3.

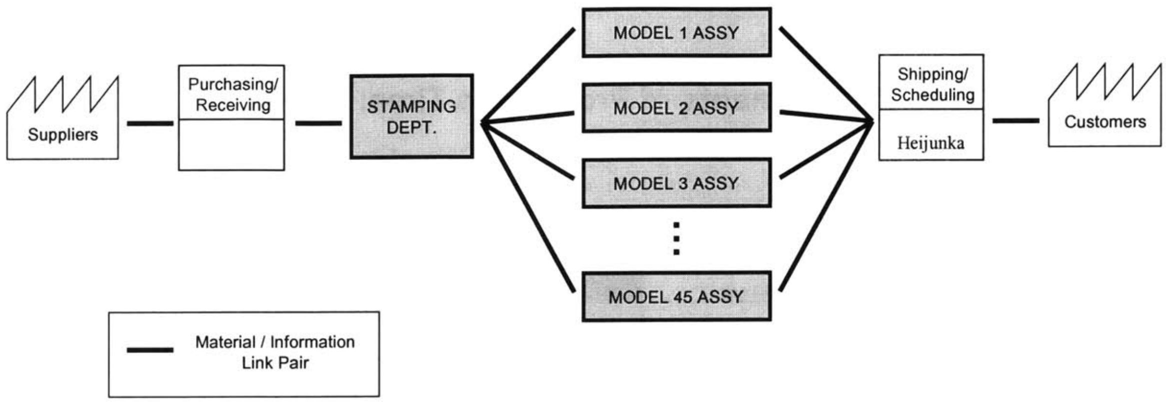


Figure 8.3
New system type: Lean cellular value streams focused for product model lines

STEPS 3 & 4: IDENTIFY CUSTOMER GROUPS AND TAKT TIME

Because this is a system *re*-design project (brown-field), accurate data is available on the history of customer demand. This information is useful in determining the takt time for each product family value stream. Each value stream has several customers, so demand volume must be aggregated into the calculation. In forming product family groups, the aggregate customer demand planning figure is used to determine the range of production volumes per shift. In the 3 shift operation, the available production time of 8 hours per shift is diminished by subtracting time for: (1) lunch, breaks and weekly meetings, (2) changeover and maintenance time and (3) overall effectiveness compensation (OEE).

A visual representation of the components of takt time is constructed in Figure 8.4 as a column broken down into 643 production cycles. Each production cycle is 37.5 seconds long (the takt time calculated based on the allowances listed above and the demand

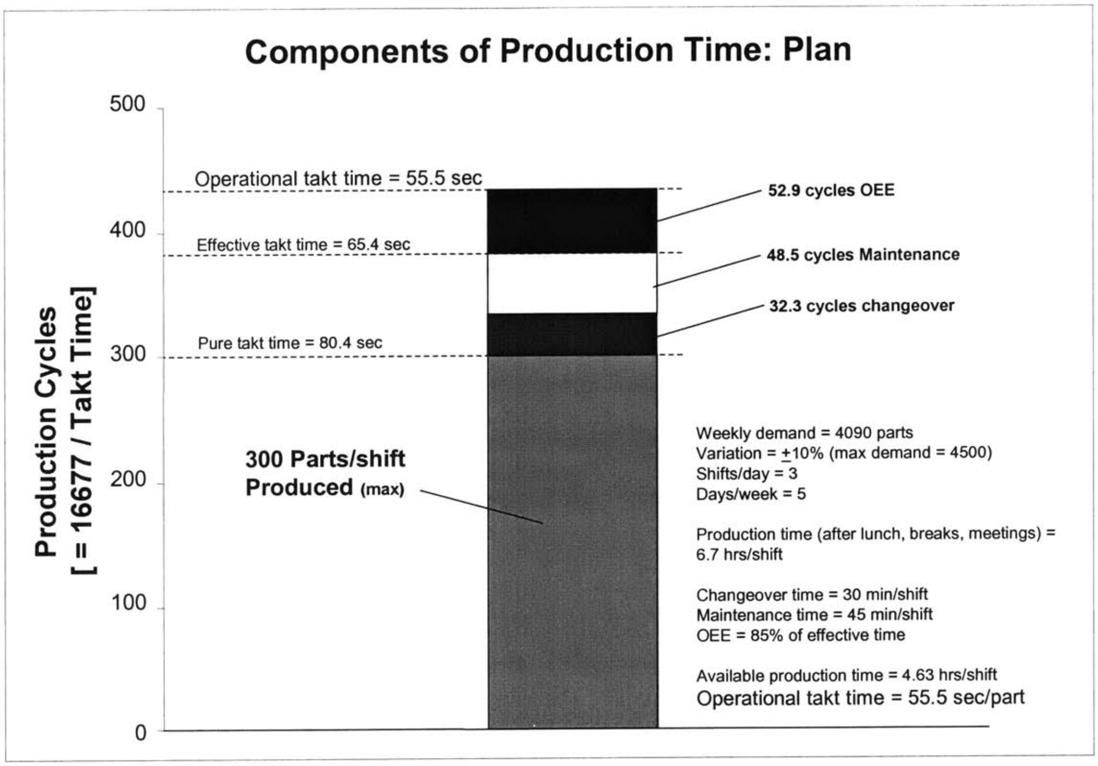


Figure 8.4
Visualization of how a shift's worth of production time is allocated

information). During 445 takt time cycles, parts are being produced. The other 198 cycles are allocated for planned and unplanned downtime. Visualizing the plan for the shift's production time in this way will become useful during implementation, in order to easily convey time-based performance feedback at the production line. Although this takt time is rather fast, it satisfies the guideline that systems with manual labor content should be designed with takt times ≥ 30 seconds.

The 85% allocation for OEE is used to compensate for unexpected production problems such as breakdowns, downtime, absenteeism, missing components or tools, quality losses or generally slow throughput. The amount of allowance for OEE is an important decision in the design process. If the OEE allowance is high, the takt time will be very fast, placing more stress on the content of work for the direct operators. Excess capacity will be built into the system, increasing both investment and operating cost. However, if the

OEE allowance is low, the burden is shifted on the system to prevent production problems. Support resources such as material handling and maintenance become critical to prevent missed shipments because of unplanned downtime. A low OEE allowance without adequate preparation will result in missed shipments to the customer. The 85% figure was chosen in this project based on historical downtime data.

STEP 5: DEFINE SYSTEM FLOW

Each value stream in the new system design can now be designed for its takt time. In the previous chapter, the design hierarchy of a production system was distilled to identify the key functional requirements and design parameters for this step of the PSDI Path. For each design decision involved in the definition of the system flow, guidelines were identified based on the design objectives. Those design decision guidelines will be applied to create a vision state value stream for the catalytic converter production system. During the following paragraphs, refer to Figure 8.6, which shows the complete vision state value stream for catalytic converter manufacturing in the Visteon plant.

INITIAL STEPS: DEFINE CONTINUOUS FLOW

The two main processing (continuous flow) elements of the system will be (1) an integrated assembly cell that combines the current sub-assembly and final assembly lines into a single cell and (2) a dedicated stamping press in the stamping department to form the shells for the assembly. It is infeasible to put the large stamping press in the integrated assembly cell because it would require a major restructuring of the plant to move and the resources to schedule, operate and maintain the stamping department are easily managed as a separate unit of the plant. Two other plant functions, (3) integrated shipping/scheduling and (4) purchasing/receiving are also modeled as value stream elements with material and information connections. These 2 plant functions interface with the customers and suppliers respectively.

STEP 5.1: BATCH SIZE AND LOT SIZE

First, the batch sizes of the material flow links are specified. *Within* the integrated assembly cell, single-piece-flow (batch size = 1) is identified as part of the subsystem design requirements in order to minimize the lot delay and to enable the separation of the operators from their machines (this design requirement will cascade to step 6 of the PSDI Path below). For the material flow links *between* the value stream elements, the batch size is standardized, but varies between part numbers. For finished catalytic converters exiting the integrated assembly cell, the container (batch) size is chosen to be a constant quantity of 72 pieces.[3] Once the finished goods container size is determined, the pitch of the system can be calculated as the multiple of the container size and the takt time. For a takt time of 55 seconds and a container size of 72 parts, the pitch of this system value stream will be 66 minutes. At most frequently every 66 minutes, production information can be released from shipping/scheduling to the pacemaker process (which will be determined later) and the status of production can be checked. 66 minutes will be the production control interval when the takt time of this system is 55 seconds.

The lot size, or leveling of production of the system is controlled by a heijunka scheduling tool in the shipping/scheduling department. Information that is received from the customer every demand interval (4 days, in this case) is sequenced to minimize run size delay and loaded in the heijunka box. Every pitch interval, a production or withdrawal authorization will be issued to the pacemaker element from the heijunka box.

STEP 5.2: LOCATION OF SWIP (DECOUPLED FLOW)

So far, the value stream consists of the following elements: suppliers and customers, shipping/scheduling and receiving/purchasing departments, the stamping process and the integrated assembly cell. As identified by the delay branch of the PSD Decomposition, SWIP inventory buffers are needed to decouple the material flow in the event of the 5 types of delays: (1) lot delay, (2) run size delay, (3) process delay, (4) transportation

---

[3] In the old system design, the finished goods pack quantity varied between model types. This results in complicated scheduling and increased variation in throughput time for the system because of the varying lot delays at final assembly. The container sizes varied between 76 and 98 pieces, which results in a ±10% variation in lead-time [Brote, et. al. 1999]

delay and (5) systematic operational delays. Material enters the plant through the receiving/purchasing department and is stored in the "coils" SWIP buffer (stamping raw materials) and the "regional" and "Line-side" SWIP buffers (OEM assembly components are stored directly at the point of use and in larger regional marketplaces nearby).

There is no buffer after assembly, because it is not necessary. The total lead time between the integrated assembly cell and the customer is expected to be very small compared to the expected response time of the customers. The expected response time of the customer, also called the *shipping window* (4 days in this case) is sufficient time for the administration, processing and shipment of customer orders. This condition calls for a build-to-order system, in which there is no finished goods inventory. Finished catalytic converters will flow directly from assembly to the shipping department and to the customer, without waiting in buffers. In order for this build-to-order system flow to be successful, the cells must achieve high quality, low throughput time variance and a low mean throughput time. The cell must be designed with low WIP and reliable processes. In good operating condition, the integrated assembly cell is expected to achieve response times as low as 1.25 hours (very small as compared to the 4 day shipping window).[4] These design characteristics cascade to Step 6 of the PSDI Path.

At this point, all of the physical *elements* of the value stream have been identified, including receiving/purchasing, stamping, integrated assembly, shipping/scheduling and the three incoming material SWIP buffers (coils, components- regional storage and components- lineside storage). The remaining steps in defining the system flow concern the material and information flows linking the elements.

STEP 5.3: FIRST PRODUCTION AUTHORIZATION POINT

To prevent variations in the amount of material throughout the system, the entire value stream is paced at from a point called the production authorization point. Leveled production information is released to the *pacemaker process* from the shipping/scheduling department with heijunka. The material flow downstream from the pacemaker process must be continuous [Rother, Shook]. In this system, the pacemaker process will be the integrated assembly cell. Production will be authorized at the assembly cell, and material will be pulled from upstream as needed by the assembly cell. In Figure 8.5, the production authorization process is marked as the "pacemaker" process. The content of the information flow link from scheduling to the pacemaker process is the production schedule.

STEP 5.4: SWIP LEVELS AND REPLENISHMENT ROUTINES

The SWIP buffers in the value stream are used to isolate production from the following disturbances: quality problems, delays from upstream processes, variability in downstream demand, unexpected stoppages and supplier reliability. The production system design compensates for these disturbances with SWIP inventory. For each component part in each of the SWIP inventory locations in the production system (line-side market, regional market and coils), the following levels are determined:

1. *Minimum stock (safety stock)*: During normal production situations, the level of inventory in the SWIP element does not drop below the minimum level. The amount of safety stock in each buffer is determined based on the likelihood and severity of production shutdowns and supplier problems.

2. *Re-order quantity (quantity used before supplier order)*: The ROQ is set by weighing the rate that part orders are sent upstream and the cost of transporting material downstream. Ideally, the ROQ is set as a single container of parts, but most ROQ's in the system are set at several containers to manage the logistics of material handling.

3. *Delivery lead-time stock*: For the line-side marketplace, the delivery lead time is negligible. Parts are moved from the larger, regional marketplace rapidly and frequently. In the regional marketplace, delivery lead-time stock is a significant

[4] Based on a takt time of 55 seconds, cell WIP of 10 parts and container size of 72 parts.

portion of the total stock. Material for the regional marketplace from outside suppliers and the batch stamping process (supplier delivery frequency ranges from 1 shift to 1 week).

The exact levels of each of safety stock, delivery stock and the ROQ varies from month to month and is set by the production controllers and management as the system improves. An example of the SWIP level calculation for a particular part type is shown in Figure 8.5 below:

Part Number:	F4TE-5E245-AA	
Part Name:	Z-SEAL	
Line Usage:	34, 35	
Daily Usage (Avg):	10960	
<u>Regional SWIP</u>		
Container Size:	1 pallet = 3120 parts	
Supplier:	ACS Inc.	
Delivery Frequency:	1 week	
Transit Time:	4 days	
Minimum (safety) stock	3 pallets	(~1 week)
ROQ	1 pallet	
Delivery lead-time stock	3 pallets	
<u>Line-side SWIP</u>		
Container Size:	1 box = 156 parts	
Supplier:	Regional SWIP	
Delivery Frequency:	20 minutes	
Transit Time:	20 minutes	
Minimum (safety) stock	1 box	
ROQ	1 box	
Delivery lead-time stock	1 box	

Figure 8.5
Sample SWIP levels for a component part

<u>STEP 5.5</u>: ESTABLISHING LINKS/LOOPS

The means for transporting material and information in the system is fully defined by designing the links of the value stream. A material information flow link and an information flow link combine to form *loops* that connect the system elements. This production system design requires nine loops. For each loop in the system, details about the mode of transportation, labor content and information processing are identified.

Figure 8.6 shows the material and information flow links in the system, and how they combine to form hybrid loops connecting the system elements.

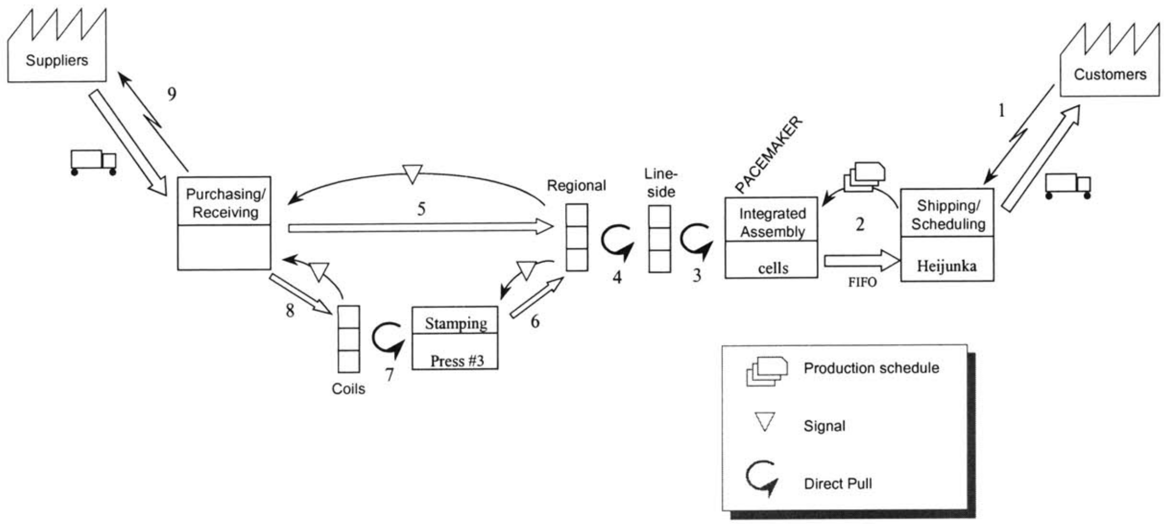


Figure 8.6
Vision state value stream for a catalytic converter product model line

In loop 1, customer orders are issued to the plant through an electronic management information system. Information on the mix and quantity of parts demanded by the customer is received by the manufacturing system via this link, and at any point in time, exact data is available for today's order status as well as forecast data for orders 3 months in advance. The forecast data is used to anticipate capacity changes in the production system. When the information is received by the shipping/scheduling department, it is leveled and used to create production schedules in the heijunka box. Material is exchanged for information and shipped to the customers via rail and truck.

Material and information movement in loop 2 is conducted by a material handler. Every pitch interval, the next set of production schedules is brought from the shipping/scheduling department to the production lines. The production schedule is exchanged for finished goods, which are brought to the shipping/scheduling department. This loop is the pacesetter loop of the system because all upstream production is triggered by the delivery of this production schedule information.

Loops 3 and 4 are shown as "direct pull" replenishment links from the line-side SWIP and regional SWIP respectively. Whenever parts are required by the assembly cell (empty material flow racks in the cell signal part requirements), a cell stocker moves parts from the line-side marketplace to the cell flow-racks. Whenever levels in the line-side marketplace drop below the level indicated by the re-order quantity (ROQ), a stocker on a forklift moves material from the regional market to the line-side market.

When material is withdrawn from the line-side marketplace, information is sent upstream in loops 5 and 6. For parts that are purchased from outside vendors, information signals are sent to the purchasing/receiving department as part of loop 5. When the replacement parts arrive from the suppliers, they are moved from the receiving/purchasing department to the regional marketplace. Loop 6 links the regional marketplace to the stamping department. Components that are manufactured in-house (shells) are stored in the regional marketplace, and information about the number of baskets of shells in the regional marketplace is sent back to the stamping department by a material handler. When this information is brought to the stamping department, it is exchanged for material that is returned to the regional marketplace.

Loop 7 is similar to loops 3 and 4 in that stamping raw material (coils) are moved from the coils inventory to the stamping department as necessary. Loop 8 is similar to loop 5. When coils are removed from the coil marketplace, a signal is sent to the purchasing/receiving department to issue an order to the suppliers.

The information that is received by the purchasing/receiving department from loops 5 and 8 are used to issue supplier orders in loop 9. This information is aggregated and sent electronically to the suppliers via the same management information system that was used in loop 1. The relationships and contracts with the supplier dictate a specific day and time at which orders are sent and parts are received in loop 9.

STEPS 6 & 7: FORM CELLS BASED ON TAKT TIME & SETUP REDUCTION

The PSD Decomposition, which maps the complete system design hierarchy from the high-level objectives, identifies all of the design objectives that cascade down to the 6th step of the PSDI Process from steps 1-5. Summarizing, the branches of the Decomposition: quality, identifying and resolving problems, predictable output, delay reduction, direct labor cost and indirect labor cost are the main functional areas that are important in subsystem design. The detailed physical design of each value stream element and link is done in steps 6 and 7, and are built on the manufacturing floor.

The cell design is a large part of the design process. Design characteristics such as quality, predictability in output, delay reduction through single piece flow and leveling (quick changeover) are achieved with a cellular approach to assembly design. The new integrated assembly cell combines the previous sub-assembly and final-assembly areas. The layout of the equipment and the line-side marketplace is shown in Figure 8.6. Machines are placed close together in a U-shaped layout to allow the operators easy access to every machine and part in the cell. The material replenishment system for the cell is integrated into the cell design via flow racks with loading access in the rear. Equipment must be designed for the cell operator, along with the standard work loop tasks that are to be done by each operator during one takt time interval. A standard work chart, showing the tasks and timing of the 7 workloop operation of cell 34 is shown in Figure 8.7. The tasks of the cell operators are paced by the takt time.

Standard work methods (not shown) for the material handlers that operate the material and information flow links of the system are also designed in detail. These tasks are paced by the pitch of the system.

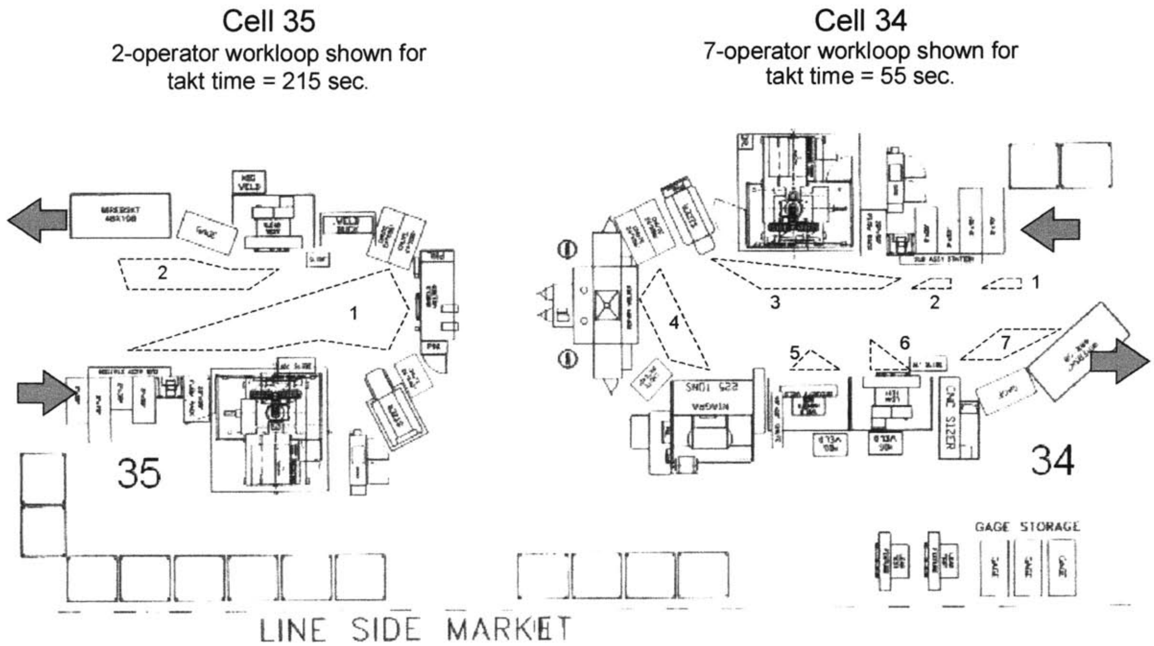


Figure 8.7
Integrated assembly cell design

Cell # 34			TIME			
#	OPERATION	STATION	Man	Walk	Auto	Comb
1	Wrap and Tape	Build Table	30	0		
2	Rings, Load shell, move	Build Table	24	2		
	Return to station			2		
3	Roll stamp	Roll Stamp	8			
	Close shells, move	Roll Stamp	4	2		
	Unload, load, cycle, move	Acro	12	2	39	
	Size, move	Sizer	12	2		
	Drop off assy, return trip	Melton		4		
4	Unload Melton	Melton	6			
	Load, cycle, move	Melton	14	2	15	
	Load, crimp	Crimper	20			
	Unload, move	Crimper	2	2		
	Drop off assy, return trip	Bracket weld		4		
5	Weld and move	Bracket weld	29			
6	Load, sec. Weld, leaktest,	Leaktest	37			
	repair weld, move					
7	Size outlet, tape, gage, move	Gage	34	2		
	Packout and return trip	Pack	6	2		

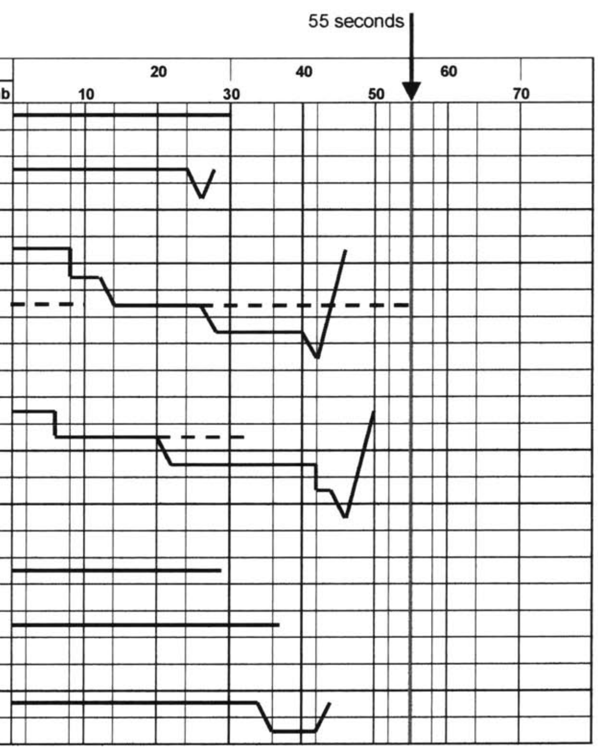


Figure 8.8
Standard work chart for Cell 34 for takt times in the range of 49 and 58 seconds/part

Setup reduction is necessary to reduce the impact of the level scheduling and more frequent changeovers. The elimination of setup tasks that require the cell to be shutdown and the minimization of manual labor content in all setup tasks occur during the 7^{th} PSDI Step. By moving the tools and fixtures necessary for cell changeovers within easy access of the cell operators, cell changeover time for the integrated assembly cell was reduced to as low as 5 minutes.

STEPS 8 & 9: LEVEL ASSEMBLY AND OPERATION WITH HIGH SWIP

Once the physical design created in steps 1-7 is built on the manufacturing floor, implementation begins at step 8 by pacing production with a level schedule. At this stage of implementation, the focus is to improve the *detailed* aspects of the cell operations, equipment, material handling and information links and SWIP elements. Keeping the flow of the system in mind, the system elements must be improved to allow for smooth flow of production information. The setup reduction efforts from step 7 should allow the system to handle more frequent changeovers and level production. In step 8, the flow in the production system begins to take shape.

Early in the implementation process, unexpected production problems will occur. The new cell design will not perform to specification at first, so excess inventory should be held in the system to compensate (before *and* after final assembly). The SWIP levels that were calculated in step 5.4 should be used as a target to structure improvement efforts. However, at this point in the implementation process (step 9), it is naïve to think that the system can perform with minimum inventory. Over time, the SWIP levels will be reduced, improving response time and holding costs as a result of improved predictability in output.

STEPS 10: TOWARDS SWIP REDUCTION

Up until this point in the PSDI Path, the production system has been designed for the high level manufacturing objectives and the detailed physical components have been assembled on the manufacturing floor. The system is now operational and the pace and mix of production are being controlled at the pacemaker process. In this step, step 10 of the PSDI Path, the functional design hierarchy (PSD Decomposition) is revisited to see what needs to be done to improve the system's performance. As the improvements are made, the SWIP levels are reduced, tightly linking the production elements.

In approaching the improvement process, it is critical that the *root cause* of problems is identified and eliminated. This is a very difficult task in managing complex systems such as production systems, particularly because of the seemingly infinite types of interactions between elements. Several approaches are used to help identify the root cause of problems. Senge proposes several "system archetypes" that map the interactions between fundamental and symptomatic causes of events in the system [Senge, 1990]. Deming discusses an iterative approach to managing improvement programs, namely the "Plan-Do-Act-Check" process [Deming, 1982]. Shingo identifies that asking the "5 Why's" to find the root cause of problems as a key tool in the Toyota Production System [Shingo, 1989]. In this project, a visual tool was created to track the key performance measures.

In this system implementation project, the most significant cause of production problems proved to be low machine uptime reliability. One of the pieces of production equipment in the cell was consistently shut down unexpectedly. More SWIP is used in this situation to buffer some of the short-lived production problems (less than 5 minutes). For each key performance measurement for this system, a tracking tool is created to monitor the current state and progress of improvement. In Figure 8.9, data on production volume and downtime is used to create a visual breakdown production time. Data is average on a weekly basis, for each cell. One column in the chart represents an average shift's worth of production time during the week. The bottom column shows the number of cell cycles during which parts were produced. Each component of the column above the production bar represents time devoted to (1) changeover, (2) machine shutdowns, (3) waiting for parts or tools to arrive, (4) scrap and (5) other unknown causes. The following three observations can be made from the chart:

(1) Machine shutdown is a much more significant cause of performance loss than waiting for parts/tools or scrap.

(2) Unknown causes of lost production becomes a significant problem in the latter weeks.

(3) This cell has a very low scrap rate.

Similar tools can be used to track the more specific root causes of production problems, such as poor quality, labor task variability, and material and information flow problems.

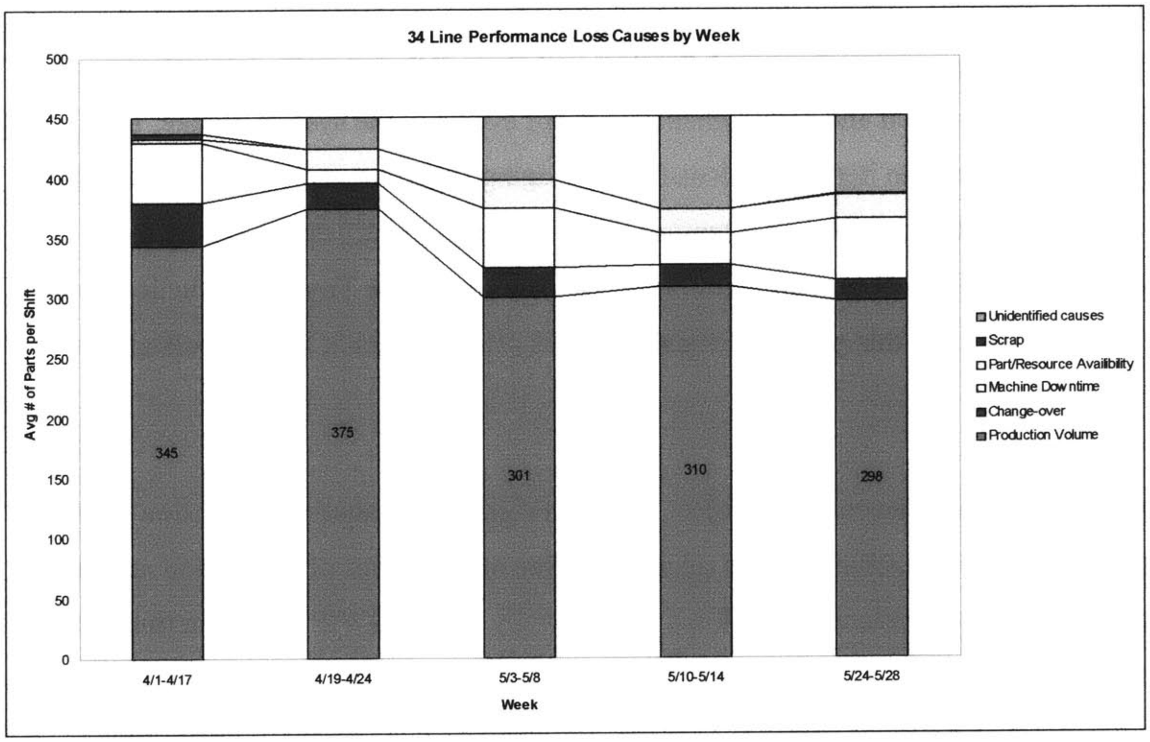


Figure 8.9
Tool used to identify the causes of performance loss at the integrated assembly cell

<u>STEPS 11 &12</u>: SUPPLIER AND PRODUCT DEVELOPMENT

The improvement efforts in step 10 were focused on the internal aspects of the production system. In moving to steps 11 and 12, the attention shifts to two external factors that are important in effective manufacturing: suppliers and product development. Now that the production system has been stabilized, supplier relationships can be improved by directly linking the supplier into the flow of the system. By giving the suppliers a reliable and level demand pattern, their time performance and operating costs can be improved. The system design technique used in this project is offered to the suppliers to aid in the integration into the flow of the system.

Integrating product development into the production system involves communicating the functional and physical hierarchy of the production system design to the product design group. The approach to production system design used in this application will create different objectives and/or constraints on the product design process, in terms of design for manufacturing (DFM).

9 Conclusion

The physical nature of production systems requires that the design and implementation process follow a structured path. Systems thinking, the notion of keeping both the high-level objectives and the interrelation of system components in mind, during every decision-making process is a necessary but complex approach to production system design. Manufacturing systems, which represent an increasingly significant part of a company's competitive advantage must therefore be designed, implemented and controlled based on standardized, structured methodologies.

Because of the various levels of complexity in analyzing production systems, the notions of level of scope, flow and focus were discussed repeatedly. Designing production systems at the level of scope of material and information flow is a critical part of translating the high-level objectives of the system into detailed subsystems and components. The system focus is identified from the important characteristics of the customers, products, process technologies, markets and industry. The way the system is focused will determine how the flow in the system is designed.

To manage the complexities in the design and implementation process, axiomatic design was applied to production system design to create the Production System Design Framework. Part of the framework is the Production System Design Decomposition, which is the design hierarchy of production systems in the functional (what to do) and physical (how to do it) domains. The Production System Design and Implementation Path is presented in chapter 4, which guides the design of production systems from the high-level objectives and focus decision, through the design of material and information flow for the system and detailed subsystem/component design, and upward through the steps of production system implementation. The PSDI Path is meant to communicate the entire transformation of objectives into a real production system. This path, when applied to real situations of production system design will help guide the design and implementation process, to be sure that the design is created with the correct types of objectives in mind and that the implementation steps occur in the correct sequence.

Mistakes in the design and implementation of large-scale production systems can be quite costly. The PSDI Path was created with the purpose of applying it to the general case production system, in the hope that it will be adapted and applied to future production system design and implementation initiatives.

In addition to the design and implementation of production systems, the control and operation of the system was discussed in terms of a feedback control model in chapter 5. This model articulates the short-term and long-term nature of analyzing the performance of the system and basing control actions on the actual vs. desired state of the system. Understanding the control of production systems in this way highlights some key aspects of the production system design process, namely that delays in feedback of control decision is costly and that the control actions must be based upon the correct high-level manufacturing strategy. Too often in the operation of production systems, the control policies are rooted in traditional inefficient ways of viewing the system. This model of the control architecture can be further developed and applied at the management level of a manufacturing organization to create an effective vision of the system. The design path, implementation path and control policy each play a critical role in the success of the production system.

During the entire PSDI Path, it is necessary to visualize and communicate the system design. In order to do this, an object-oriented modeling environment for manufacturing systems was proposed in chapter 6. This model consists of 4 major objects: continuous flow elements, SWIP elements, material flow links and information flow links. By combining these objects into system value streams, the material and information flow in the system can be mapped. Further development of this modeling environment may result in a useful tool for designers to create, analyze and communicate the manufacturing system design to many people. Viewing manufacturing systems in the manner presented in chapter 6 is aligned with the manufacturing system design path, in that the functional objectives of the system cascade from high-levels to low-levels of detail. Also, this objet-oriented modeling environment allows one to easily visualize the *flow* in the system.

Defining the flow in at the linked-cell level of scope is a critical part of the PSDI Path because it serves as the link between the high-level objectives and focus decisions and the detailed design of low-level system components. In chapter 7, the design hierarchy was viewed in terms of the material and information flow in the system, creating a set of functional requirement and design parameter pairs that identify how to simultaneously achieve the manufacturing functions of quality, problem solving, predictability, delay reduction, cost reduction and investment reduction. Expanding on the part of the PSDI Path, a procedure was presented in chapter 7 that highlights the design tasks for designing the material and information flow in the system. For each design decision at this level of scope in the system, the issues and tradeoffs in effective system design were discussed.

Appendix A – The PSD Decomposition

The following figures show the functional requirements, design parameters and performance measures in the Production System Design Decomposition. The decomposition shown here is Version 5.1, created 1999. First, the entire PSD Decomposition is shown. The subsequent figures are portions of the decomposition displayed at larger size. Each pair of boxes in the decomposition shows a functional requirement and its corresponding performance measure, along with the proper design parameter. Dashed lines signify a relationship between a DP and an FR. If a dashed line connects DP_x to FR_y, the DP_x (and some DPs below DPx in the decomposition) influence the ability to achieve FR_y. The colored areas of the decomposition represent branches of the decomposition.

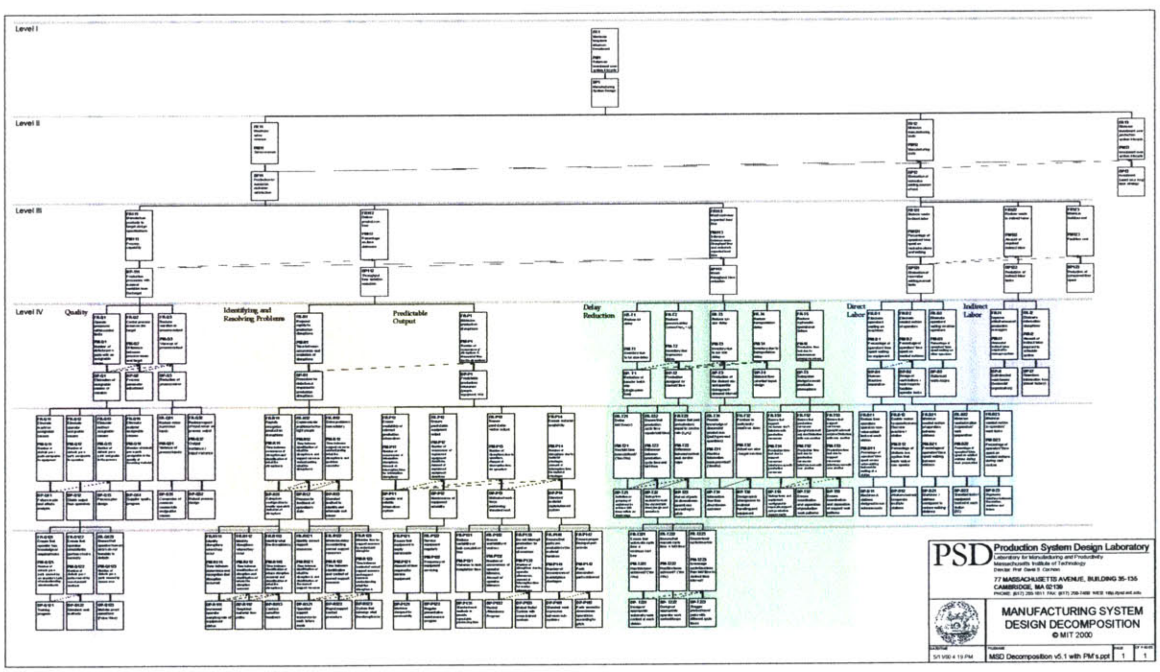


Figure A1
The PSD Decomposition

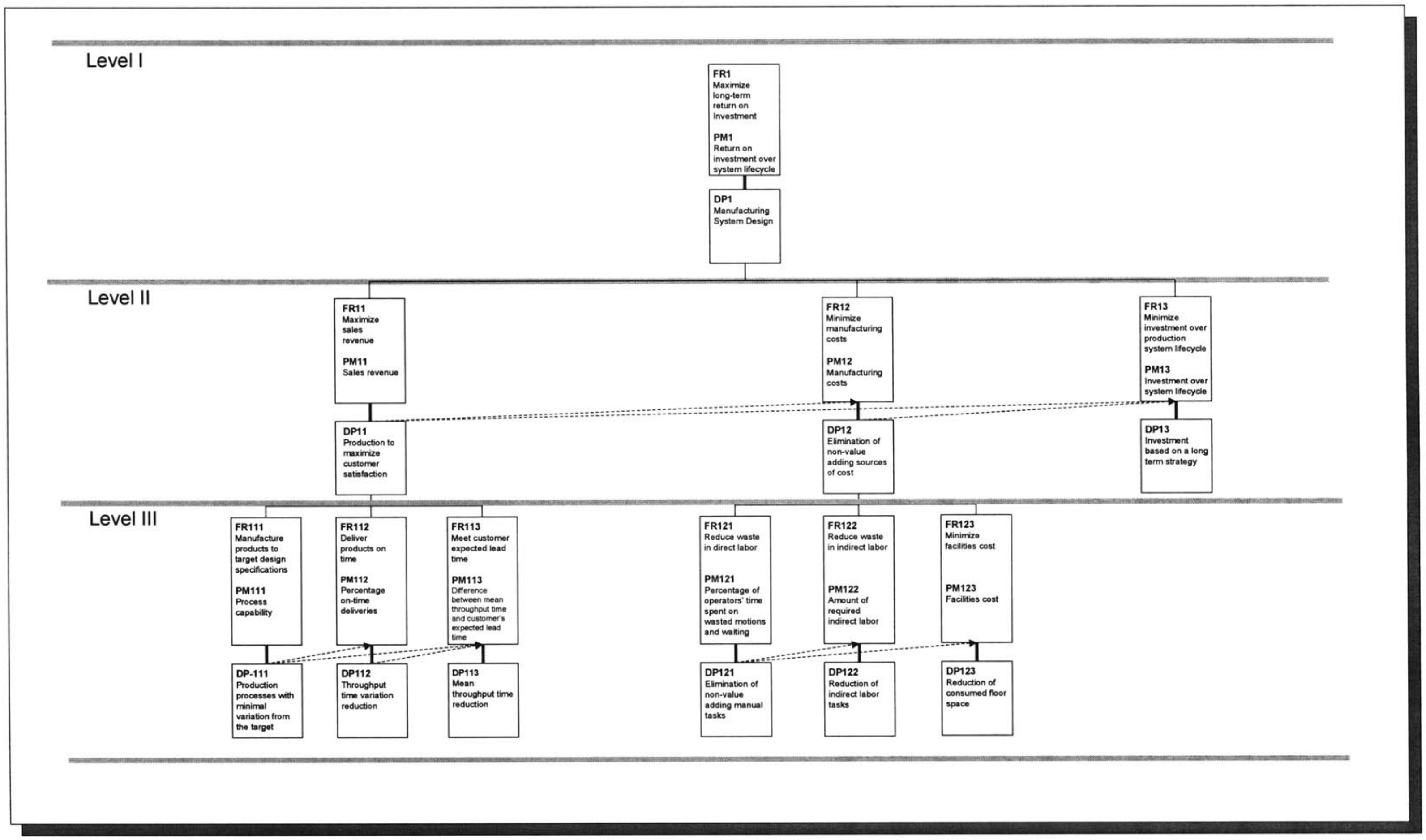


Figure A2

Levels I-III of the PSD Decomposition

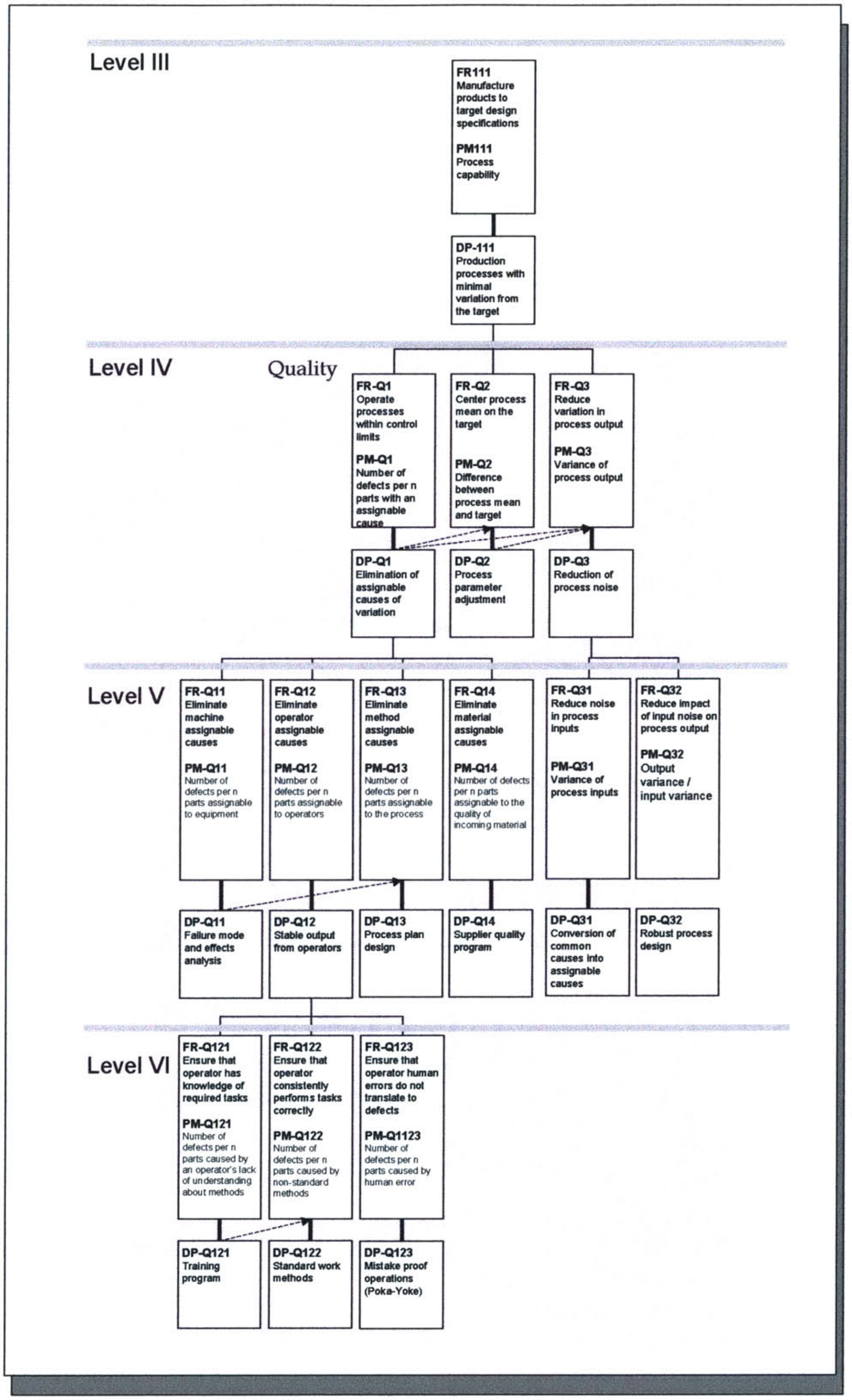


Figure A3
The Quality branch of the PSD Decomposition

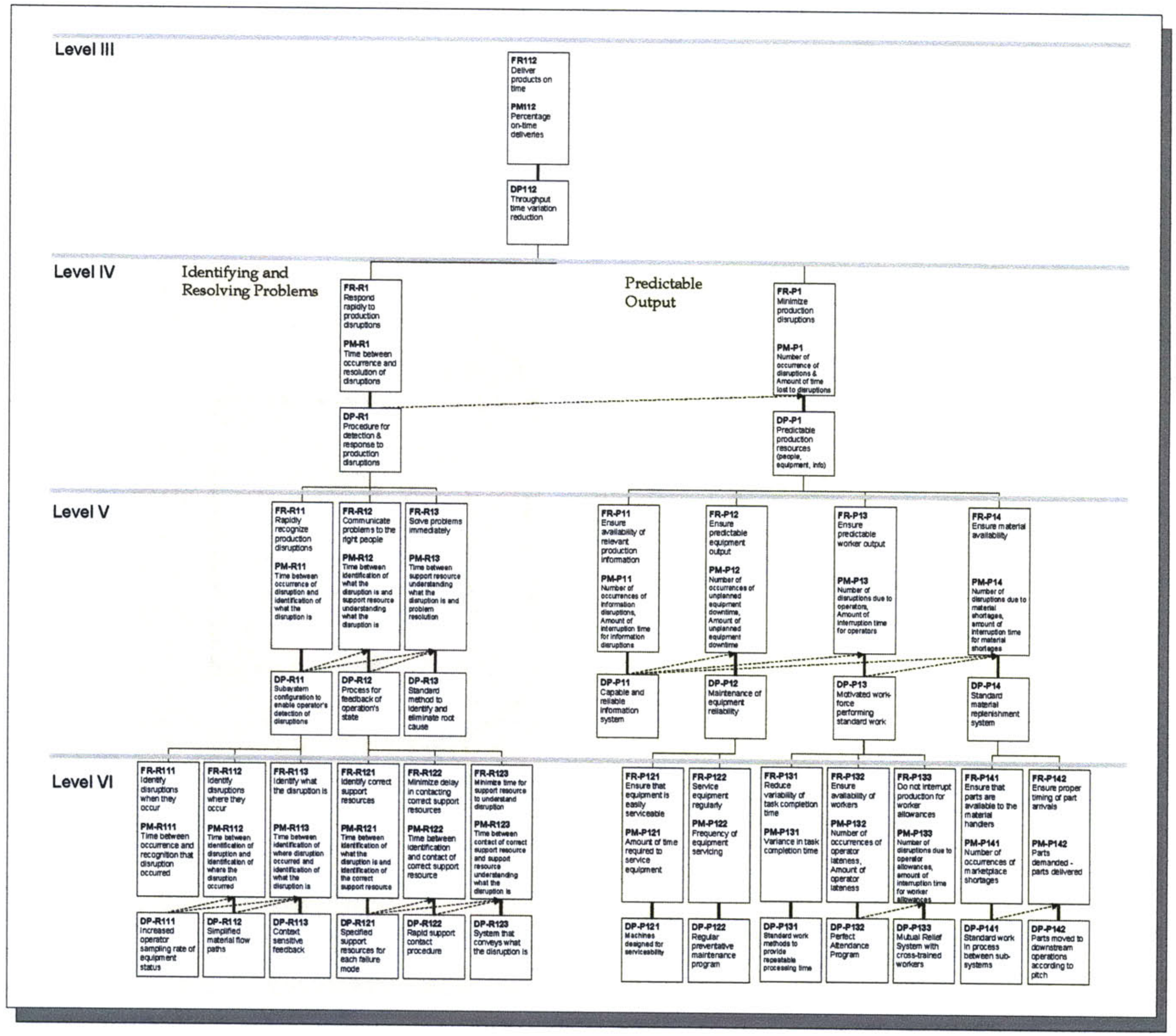


Figure A4

Decomposition of FR112 "Deliver Products on Time" into the Identifying and Resolving Problems and Predictable Output branches of the PSD Decomposition

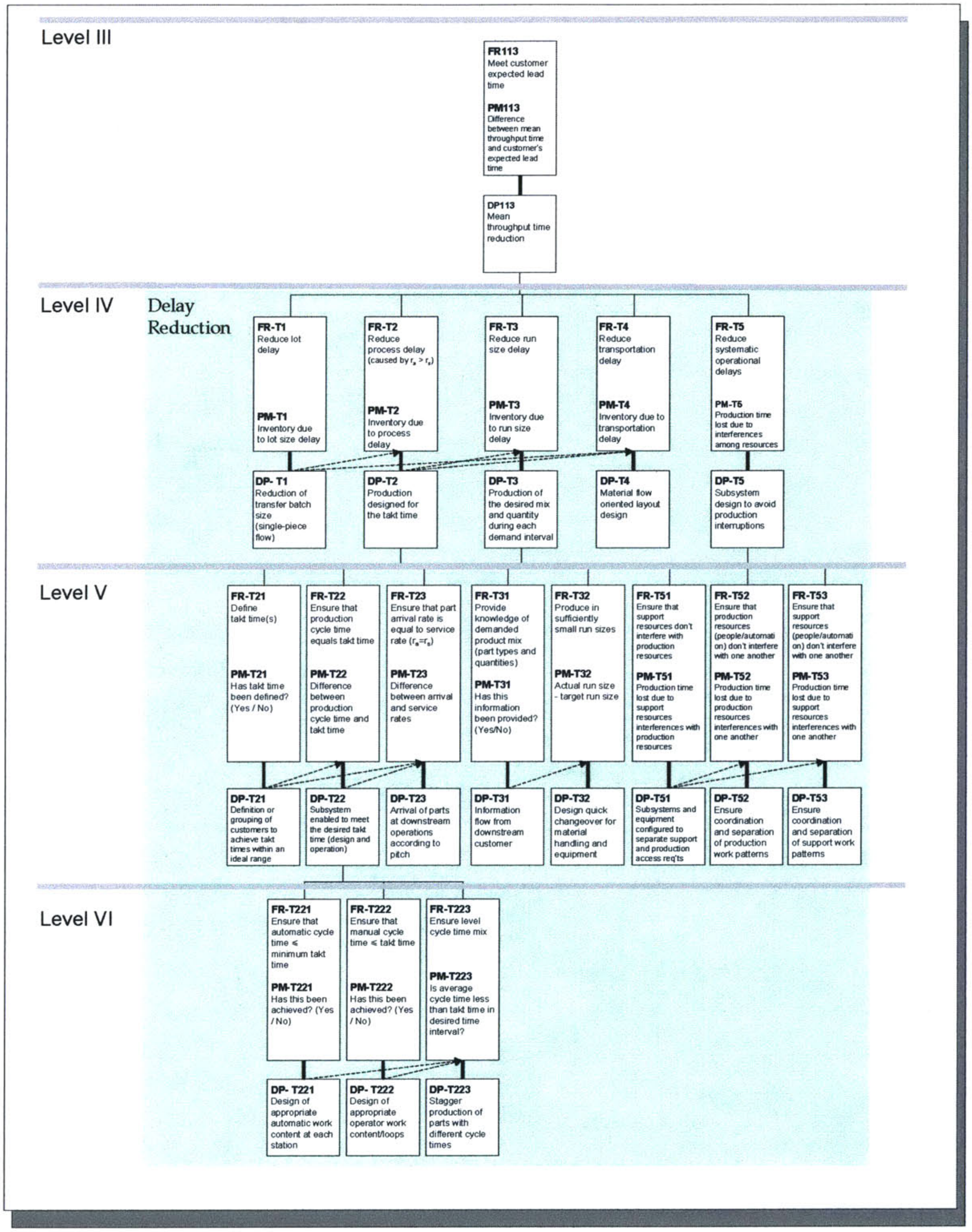


Figure A5
The Delay Reduction Branch of the PSD Decomposition

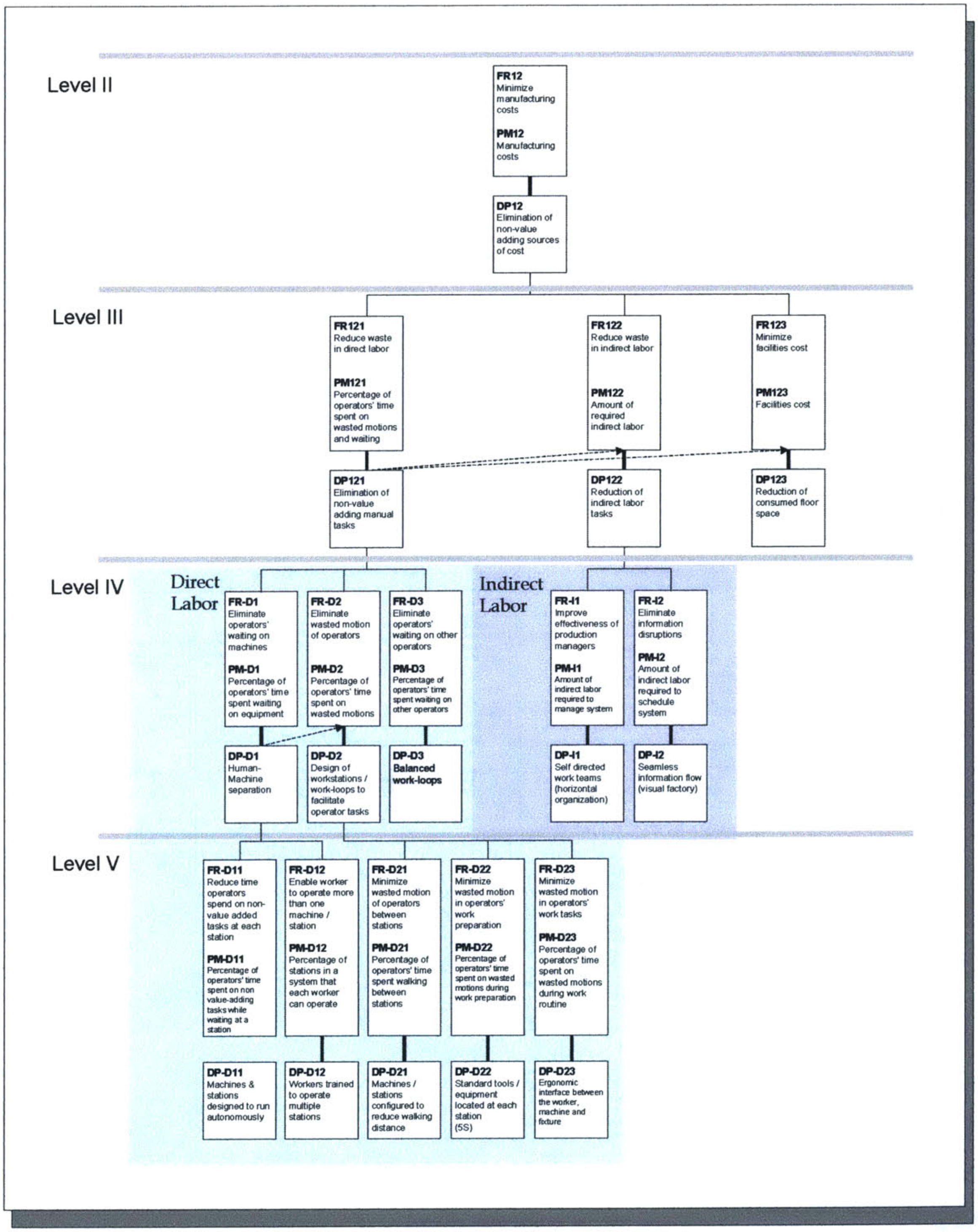


Figure A6

Decomposition of FR12: Minimize manufacturing cost into the 2 cost branches of the PSD Decomposition

Appendix B – The PSD Design Matrix

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CAMBRIDGE, MA 02139

Manufacturing System Design Matrix © MIT 1999

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		DP-Q1	DP-Q2	DP-Q3	DP-R1	DP-P1	DP-T1	DP-T2	DP-T3	DP-T4	DP-T5	DP-D1	DP-D2	DP-D3	DP-I1	DP-I2	DP123	DP13
		DP111			DP112		DP113					DP121			DP122		DP123	DP13
		DP11										DP12						DP13
		DP1																
FR1 / FR11 / FR111	FR-Q1	X																
FR111	FR-Q2	X	X															
FR111	FR-Q3	X	X	X														
FR112	FR-R1				X													
FR112	FR-P1	X		X	X	X												
FR113	FR-T1						X											
FR113	FR-T2	X		X	X	X	X	X										
FR113	FR-T3							X	X									
FR113	FR-T4					X	X	X		X								
FR113	FR-T5					X					X							
FR12 / FR121	FR-D1					X				X	X	X						
FR121	FR-D2					X	X			X	X	X	X					
FR121	FR-D3					X	X	X		X	X			X				
FR122	FR-I1					X	X					X		X	X			
FR122	FR-I2	X			X	X				X	X					X		
FR123					X	X		X	X	X			X				X	
FR13					X	X		X	X								X	X

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