Applicability of Toyota Production System to Commercial Airplane Manufacturing

by

Arthur James Raymond

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Submitted to the Department of Mechanical Engineering
and to the MIT Sloan School of Management
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Signature of Author ______________________________
Department of Mechanical Engineering
MIT Sloan School of Management
May 15, 1992

Certified by ______________________________
David E. Hardt
Professor of Mechanical Engineering
Thesis Advisor

Certified by ______________________________
James M. Utterback
Associate Professor of Engineering
Thesis Advisor

Accepted by ______________________________
Ain Sonin
Chairman, Committee on Graduate Students, Mechanical Engineering

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ABSTRACT

In the 1980's the Toyota company has been extremely successful in expanding its world-wide market share with high profitability. Toyota's unique manufacturing principles and methods such as Just-In-Time, visual control, and standardized work, (collectively referred to as the Toyota Production System, TPS), are often credited as the primary source of Toyota's success. As a result, many manufacturing companies have studied TPS, some applying it with success to their own manufacturing operations.

TPS was developed in a high volume manufacturing environment, and the companies adopting TPS are generally high volume manufacturers as well. The purpose of this thesis is to investigate the applicability of TPS to low volume industry, specifically to commercial airplane manufacturing.

The investigation is divided into two sections

1. Applicability of TPS in general to the type of product, manufacturing processes and culture found in a commercial airplane manufacturer
2. Applicability of TPS to a specific factory and manufacturing process, namely the manufacture of wing skin panels

The basic conclusions drawn from the investigation are:

- TPS implementation will be different for each plant and must be tailored for each plant's particular processes and products.
- TPS is, in the near term, more applicable to fabrication operations than it is to coordination or assembly operations.
- Application of TPS to the manufacture of wing skin panels results in a mixed-model, fixed-sequence process, with resulting inventory and flow time reductions of 60 to 80%.

Thesis Advisor:	David E. Hardt
Title:	Professor of Mechanical Engineering
Thesis Advisor:	James M. Utterback
Title:	Associate Professor of Engineering

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CHAPTER 1

INTRODUCTION

Toyota is considered to be the world's most efficient automobile manufacturer. It's manufacturing philosophy and techniques, collectively referred to as Toyota Production System (TPS), are being emulated by manufactures around the globe. This thesis investigates the applicability of TPS to low volume, non-automotive industry, specifically, to the manufacture of commercial airplanes at The Boeing Company. The investigation was prompted Boeing's interest in TPS as well as a growing awareness in Boeing that the company's manufacturing operations must improve efficiency in defense against growing competition and the imminent entry of an Asian competitor. The goal of this thesis research was to evaluate the applicability of various aspects of TPS to Boeing's commercial aircraft manufacturing operations and, if appropriate, to recommend immediate applications. The recommendations presented are to be a springboard for subsequent LFM thesis projects.

Next is an outline of this thesis, followed by background information on the history of the Boeing and Toyota companies, a summary of TPS concepts, and a comparison of the two companies' products (airplane vs. automobile).

Outline of Thesis

The first portion of this thesis (Chapter 2) presents the concepts of TPS and discusses their applicability to Boeing in general terms. The analysis concludes that TPS is, in the near term, more applicable to fabrication operations than it is to coordination or assembly operations. It also concludes that TPS implementation will be different for each plant and must be tailored for each plant's particular processes and products.

The second portion of the thesis (Chapters 3 and 4) presents the results of a detailed investigation of TPS applicability in the plant that manufactures wing skin panels. Chapter 3 proposes changing the plant's production method to a mixed-model, fixed-sequence process and presents an implementation plan. Chapter 4 presents an analysis of resulting inventory and flow time reductions (60-80%).

Conclusions are summarized in Chapter 5.

History of The Boeing Company

The Boeing Company began when the Pacific Aero Products Company was founded in 1916 as "a general manufacturing business...especially to manufacture aeroplanes and vehicles of aviation...operate a flying school and act as a common carrier of passengers and freight by aerial navigation."[1] Based in Seattle, Washington, the company proceeded to do just that, building a vertically integrated company that included engines, airplanes, freight and passenger airlines. But in 1934 the Federal government ordered the company broken up for anti-trust reasons, spinning off engines and airlines into separate companies, leaving Boeing to just build airframes.

Boeing has had a long history of excellence and technical innovation. This innovation, practiced largely in military airplane programs such as the B-17 and B-52 bombers, led to the world's first commercial jet transport, the 707, in 1954 and a

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[1] E. E. Bauer. Boeing in Peace and War. (Enumclaw WA: TABA Publishing, 1990) p19.

subsequent transformation of the airline industry. Since then, Boeing has dominated commercial aviation, commanding about 65% of the world market for many years.[2] Today, there over 5,000[3] Boeing jets in service in 120 nations[4].

Ever since Boeing initiated the commercial jet age in 1954, it has faced strong competition. Until the 1980's this competition has been mainly from other U.S. manufacturers. One competitor, Lockheed, was driven from the market in the 1970's by the failure of its L-1011. Another, McDonnell Douglas, has been a marginal contender since their DC-10 was discontinued in the late 1980's. Since 1970, a new contender has been rising, Airbus Industries. It may prove to be the greatest challenge yet to Boeing's dominance.

Competitive Challenge

Airbus has enjoyed significant backing from several European governments who are determined to see Airbus provide jobs and an aerospace technology base for Europe. Since its founding in 1969, Airbus Industries has received almost $20 Billion in government subsidies to cover its consistent losses. However, industry observers assert that Airbus is close to break-even volume and has become a legitimate competitor.

Despite its consistent losses, Airbus has gradually penetrated the market and now claims a 30%[5] market share. Most worrisome is that Boeing is losing longtime customers to Airbus. For example, Northwest Airlines for years flew exclusively Boeing airplanes,

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[2] Carolyn Corvi, MIT lecture, 4/24/1992.
[3] Bauer, p333.
[4] Boeing Chairman Frank Shrontz, quoted in Boeing News 7/26/91 issue.
[5] Corvi.

but in 1986 it signed an agreement to purchase up to 100 A320s, an Airbus plane comparable to Boeing's 737-400.[6] Until recently, Boeing had not taken Airbus seriously, but they clearly are today.

As demonstrated by Airbus, the airplane market is becoming a price competition between Boeing and world governments. The next competitor expected to enter the fray is either Japan, Korea, or a Southeast-Asian consortium, most likely government subsidized. Japan's MITI has publicly identified commercial aircraft as one of its key objectives for the next decades. MITI has organized a consortium of Japanese aerospace companies in a coordinated program to capture and develop technology and gradually enter the airplane industry. Several of these companies are already significant Boeing suppliers, manufacturing many parts, including fuselages for the 747 and 767 airplanes. They are also risk-sharing partners for Boeing's new 777, involved in design and construction of the fuselage sections and other major components.

Boeing's own success may turn out to be more threatening than any competitor. By the mid-1980's, "The signs of self-satisfied complacency were all too obvious to top management: increased absenteeism, customer complaints on quality, defective parts, missed deadlines, and a general laissez-faire feeling that prosperity was finally guaranteed. It was the kind of climate that was more difficult to address than bona fide adversity."[7] Also contributing to this problem was the increasing life cycle of commercial products. Building 747's for twenty years has been quite different from experiences in the company's youth when projects were much shorter "In commercial airplanes, ... work had become compartmentalized and routine. Those larger-than-life challenges [such as the 747 launch and the Minuteman missile program] had been replaced by the humdrum of the production

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[6] Bauer, p329.
[7] Bauer, p331.

line. Wages and fringe benefits had become more sharply focused than the historic dedication to excellence of performance."[8]

Boeing managers realized that complacency combined with the threat of increased competition could knock the company from its position of market dominance, just as it nearly did for General Motors in the 1970's and 1980's. In response to this concern, then-chairman Malcolm Stamper launched a new program, Operation Eagle, in 1985. "Its goal was no less than to change the culture of the company from the more authoritative top-down type to a more participative type."[9]

In 1986 Boeing President Frank Shrontz introduced a new program called CQI, Continuous Quality Improvement. At first, many in the company figured it was just another fad program which would soon be replaced by yet another---but it stayed. In 1992 it was still in place and was gaining strength. I spoke to many factory workers and managers who felt it is truly changing the way they performed and thought about their jobs: work areas were being redesigned, some workers were being cross-trained, employee problem-solving teams were being employed, SPC programs had been initiated, etc.

In addition to increased employee involvement through CQI, the company is pursuing reform in both product design and manufacturing in an effort to cut costs and better provide for customer needs. There has been significant change in the product design process, embodied in the new 777 airplane. It is being designed 100% on computer, totally digital. Also, the airlines are more involved than ever before, helping to define preliminary specifications and optional internal configurations. But the area in which Boeing has yet to significantly change is the manufacturing process.

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[8] Bauer, p335.
[9] Bauer, p331-2.

Origin of this Thesis Project

Throughout the Boeing company, employees have begun to question manufacturing practices and strategy, feeling a significant redirection is needed in order to remain competitive. Many have been asking how should Boeing build airplanes in the future. Having been number one for so long, it is difficult for Boeing to commit to serious external benchmarking. Boeing has had major Japanese suppliers for many years, but hasn't yet seriously considered what can be learned from these suppliers. For example, Boeing's Renton plant assembles fuselage for the 737 and 757, while Japanese suppliers manufacture fuselages for the 747 and 767. Yet despite much inquiry, I could find no evidence that the Renton and Japanese engineers or workers communicated on techniques, which is surprising considering that the Japanese panels are acknowledged to be far superior in quality.

Fortunately, this insular attitude is beginning to change. Since 1989, Boeing has conducted a program to study Japanese companies. This program includes Japan Study Missions, which consist of a six to eight week study course on best manufacturing practices followed by three weeks touring factories in Japan. Several groups have taken the trip, including all the top executives, as well as engineers, staff, and middle managers.

A common conclusion made by participants in the Japan Study Missions is that Toyota is the most impressive and has the best manufacturing system. Because of this interest and other attention TPS has received in the past decade, I was recruited to conduct an academic analysis of the applicability of TPS to Boeing's commercial manufacturing operations.

Toyota - History and TPS

Toyota entered the automobile industry in 1933,[10] building trucks for the Japanese army. After W.W.II Toyota switched to car production and grew slowly. In the 1950's, an engineer named Taiichi Ohno, rejecting the capital-intensive manufacturing methods of Ford, GM and Nissan, began developing the now-famous Toyota Production System. Toyota continued to grow through the 1960's and 1970's with the expanding Japanese economy, and became a major exporter in the 1970's and 1980's.

Toyota credits much of its success to its manufacturing philosophy and methods, which have allowed it to rapidly become the largest auto producer in Japan and the third largest in the world. This system, called the Toyota Production System (TPS), is described below, beginning with its underlying concepts and proceeding to the practical methods employed in daily operations. This description of TPS comes largely from Yasuhiro Monden's book, Toyota Production System, Practical Approach to Production Management. It is presented as a hierarchy of concepts with each subsequent level getting closer to the plant floor level of operations. My understanding of this hierarchy of ideas is illustrated in figure 1.1.

TPS Goal: Elimination of Waste The ultimate goal of TPS is maximizing productivity, and the primary approach for accomplishing this is the reduction of costs by eliminating waste (waste being defined as any unessential or redundant resource or activity). Waste is attacked in the following three ways:

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[10] Cusumano, Michael A. The Japanese Automobile Industry (Technology & Management at Nissan & Toyota). (Harvard East Asian monographs, 122) (Cambridge MA: Harvard University Press, 1989) p67.

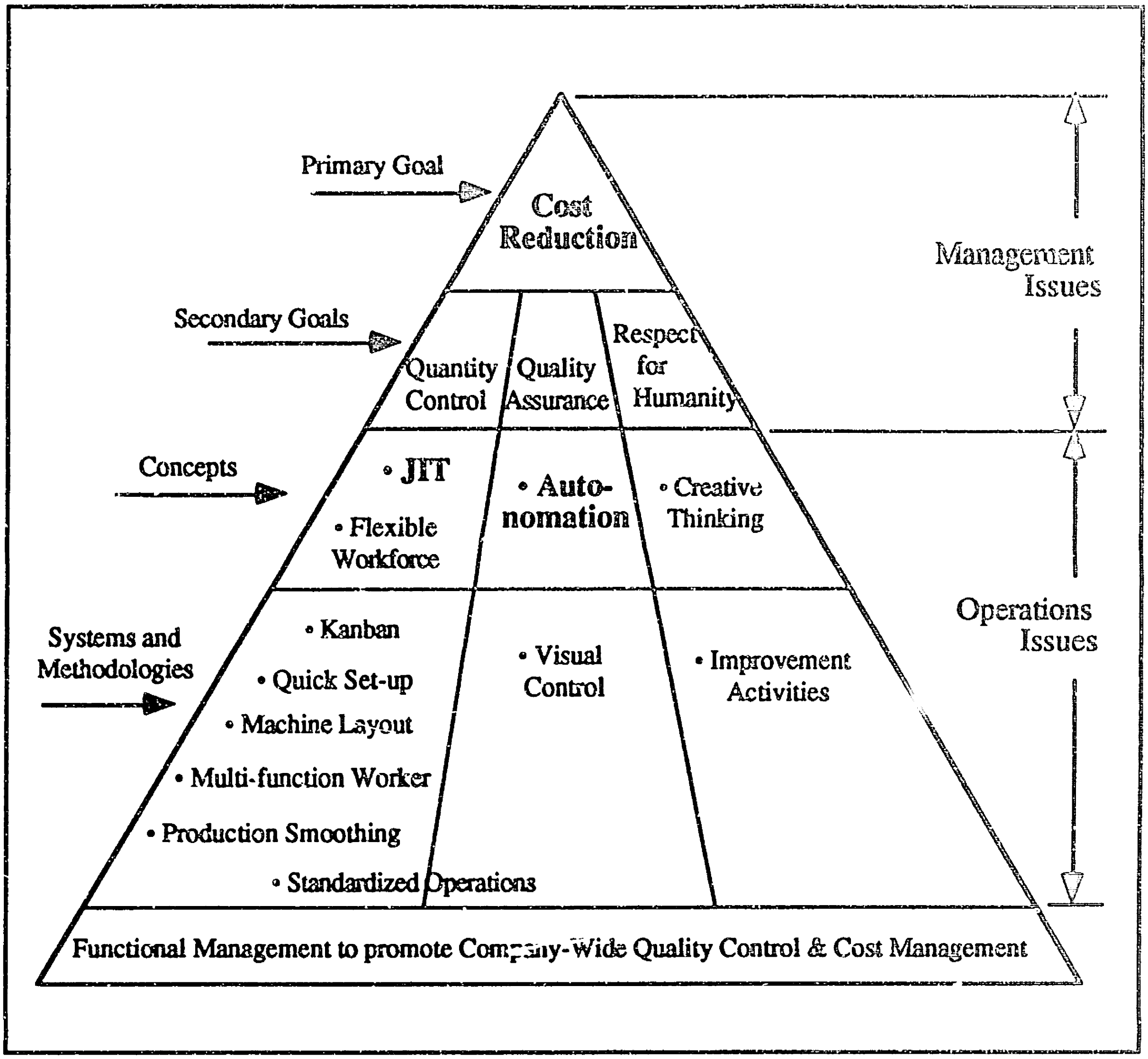

Figure 1.1 Hierarchy of TPS concepts

1. Quantity Control By controlling the quantity of inventory, the manufacturing system can better adapt to fluctuations in demand

2. Quality Assurance Each process must supply only good products to its subsequent processes

3. Respect for Humanity. People are recognized as a vital resource for attaining cost objectives

TPS Concepts The three-pronged attack on waste is guided by diligent application of the following four concepts:

1. Just-In-Time Production (JIT) Producing only the type of products needed, only when needed, and only in the quantity needed, which reduces inventory and lead time
2. Autonomation Automatic defect control supports production by preventing defective products from flowing to and disrupting subsequent processes
3. Flexible Workforce Varying the number of workers in response to changes in demand reduces labor waste
4. Creative Thinking Continuous improvement is achieved through capitalizing on workers' suggestions

TPS Techniques To apply the preceding four concepts in daily operations, Toyota has developed the following eight systems and methodologies:

1. Kanban An information system that controls material conveyance and replenishment to support JIT
2. Production Smoothing Production is planned to minimize short-term variation in demand and to adjust for long-term variation in demand
3. Quick Set-up The ability to quickly modify production machines and processes to run a new part; this allows frequent set-ups and smaller lot sizes, which lead to reduced production lead times and lower inventory levels
4. Standardized Work Documentation and standardization of production tasks; this assists in line balancing and improvement activities
5. Machine Layout and Multi-function Workers Machines are arranged and workers trained so that the number of workers can be varied significantly in response to changes in demand; this increases workforce flexibility and productivity

6. Improvement Activities Group-based suggestion system that increases worker morale by getting everyone involved in the drive to eliminate waste

7. Visual Control Posters, labels, color-coding, signal lights, etc.; these assist workers in preventing defects; the goal is to make each operation easily understood at a glance

8. Management Systems Cross-functional, policy-setting management teams to promote company-wide quality control and cost management

Comparison of Automobiles, Airplanes, and their buyers

Before considering the application of Toyota methods to Boeing, the reader should contemplate the tremendous differences between the two products and their markets. Figure 1.2 compares various characteristics of cars to those of airplanes, as well as their design and manufacture.

Differences in the markets for these two products are as significant as the differences in the products themselves. Whereas cars are generally sold to individuals in the country of manufacture, airplanes are purchased by large companies all over the world. Many airlines are government owned or controlled, so the purchases can become political.[11] There are many car companies competing for sales, but only three major commercial airplane manufacturers in the world (Boeing, Airbus, and McDonnell Douglas). Cars compete on many levels such as styling, image, cost, etc., but airplanes have become commodity products, competing basically on purchase and operating costs.

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[11] Governments often require Boeing to transfer some production to their country as a condition of purchase. For example, China builds 737 tail fins as part of their contract for purchasing 737s.

	Toyota Car	Boeing Airplane
Development cost	$1 to 2 Billion	$2 to 4 Billion[12]
Development time	3 to 5 years	3 to 4 years
Number of parts	Approximately 20,000	Approximately 3,000,000
Production rate (for one model)	50,000 to 200,000 per year	50 to 200 per year
Production run	4 to 6 years	Approximately 20 years
Price	$8,000 to $40,000	$20 to 100 million
Service life	10 years	30 years minimum

Figure 1.2 Comparative statistics for automobile and airplane

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[12] Dari Shalon, "Boeing versus Airbus", MIT Sloan strategy paper, 1991. p7.

CHAPTER 2
TPS APPLICABILITY

This chapter addresses the primary question of the thesis: how applicable are the TPS practices to Boeing's commercial manufacturing operations? What can Boeing learn from Toyota? Where is improvement most likely to occur from implementing TPS methods? Which TPS methods are most appropriate for the various parts of the company (fabrication, final assembly, engineering, support services)? In what fashion should learning and implementation be pursued? What action plan should be followed? This chapter seeks to answer those questions and is organized as follows:

1. Discussion of how each company's assumptions and principles determine its business practices and processes

2. General applicability to Boeing of specific TPS principles and techniques

3. Shop-specific applicability of TPS, including specific implementation plans

4. Conclusions

5. Recommendations and follow-up research

Business System Determines Form

The question of TPS applicability must be addressed at two levels: (1) cultural/managerial, and (2) operational/technical. The first level refers to the alignment of TPS concepts with Boeing's current managerial style and company culture, which is the most crucial issue and the most difficult to address. The second level refers to the ability of Boeing's production system to implement a TPS practice given the current technical constraints of product design and manufacturing processes and systems.

The distinction between levels is important, since it is the first level (management mindset and culture) that determines the nature of the second (operational and technical). In both Boeing and Toyota, the form of processes and equipment follows from the company's objectives and culture. Each culture leads to system design decisions and determines the physical constraints the company is willing to accept. In both companies, a decision is made, and physical systems must be designed to support it.

Because culture and managerial atmosphere drive the company's decisions, managers must consider the fit between imported techniques and current working environment before a set of techniques can be transported successfully f[illegible]ne industry to another and from one company to another. The objective of this thesis i[illegible] to address the differences between Japanese and American culture, or between work ethics, etc. The focus is on factory operations techniques, yet the reader must remember that the techniques require an appropriate environment to be successful. Before launching into a description of TPS and Toyota's motivations, a description of Boeing's motivations[13] is presented. This thesis does not intend to judge or analyze these motivations, but listing them may help the reader understand Boeing's current system. (Caveat: some of these beliefs and practices

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[13] Based on my observations.

are currently changing as the management gradually begins to look at the business in a new way, one that is increasingly compatible with TPS ideology.)

Boeing assumptions:

- Schedule is paramount. As in some other mass producing companies, stopping the assembly line is sufficient cause for career redirection.
- High inventory levels are acceptable. Considered a cost of doing business, they guarantee schedule will be made.
- Organizations should be centralized. There are always benefits to centralization, for economies of scale and for developing technical expertise.
- Machines are unreliable and prone to breakdown, especially old ones.

Boeing practices:

- Performance measurement is based on labor efficiency. There are continuous efforts to measure and reduce labor.
- Scheduling system is extensively computerized.
- Generous amounts of flow time are scheduled, with time cushions between operations. This also results in large inventories between operations.
- Plants are managed as job-shops. Most fabrication shops are in fact job shops, but even those which could function as flow shops are scheduled and monitored as if they were job shops.
- Workforce is specialized, with extensive division of labor.

GENERAL APPLICABILITY OF TPS TECHNIQUES

Toyota strives to improve profits through waste elimination efforts. These efforts focus on two key areas: quantity control (reducing inventories), and quality assurance (reducing scrap, errors and rework). So Toyota's top three goals (waste elimination, quantity control, and quality assurance) are somewhat different from the stated goals of most US companies (cost, quality, and schedule). The similarities and differences will be addressed as TPS concepts are discussed on the following pages. First, the primary goal of waste elimination is discussed. Second, the JIT concepts and tools for controlling the amount of inventory in the system are presented. Third are presented the concepts and tools for assuring quality in the process. Fourth is a discussion of HRM concepts, concluding with the management structure which assures harmony between the elements of TPS. Figure 1.1 presents a hierarchy of TPS concepts, to which the reader may wish to refer during the following applicability discussion. The pyramid's upper entries are primary goals of TPS, while the lower entries are specific techniques.

As each particular TPS concept or technique is addressed, the following issues are addressed:

1. Description of the TPS concept/technique
2. Boeing's current comparable method
3. Applicability of the TPS concept/technique in Boeing
4. How it could be implemented in Boeing operations

Waste Elimination

Mass producers typically seek increased sales as the means of improving profits. While Toyota certainly welcomes increased sales, the company sees cost reduction as a more sustainable means to improve profits. Toyota involves all employees in a continual effort to reduce its cost structure through the elimination of waste. Of course, such a waste elimination mindset can help Boeing reduce its cost structure too, and there is some recognition of this at various levels in the company. Deane Cruze, Boeing Commercial Airplane Group V.P. of Operations said TPS can succeed in Boeing by the application of one idea: the elimination of all non-value added activities.[14]

Quantity Control

Toyota's approach to quantity control is the main concept that differentiates it from mass production, and it has led to some of the most important TPS concepts, notably Just-In-Time. "Quantity control" may appear conceptually similar to the mass production emphasis on producing to schedule, but it is not. Schedule driven companies, such as Boeing, are concerned that an activity is completed by a certain date, and they build control systems to track progress toward completion. Toyota, in contrast, focuses its efforts on controlling the amount of inventory in the system rather than on the completion schedule of a production run.

When Boeing schedules a job, it sets the desired completion date and schedules backwards until the required starting date is determined. Then the job is tracked through the manufacturing system to determine how well its manufacture conforms to schedule. In

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[14] Conversation, August 1991,at Boeing corporate headquarters.

general, a component manufacturer can be penalized for late deliveries, but is never penalized for being early or for having excess inventory in the system. As a result, jobs are started ever earlier and the work-in-process piles ever higher. For the suppliers and fabrication shops, work-in-process and extra flow time provide a welcome safety net.

At Toyota, however, inventory and flow time are seen as waste, and the objective is to eliminate them. Production systems are analyzed and modified to operate with decreasing levels of inventory. As a result, Toyota is able to minimize the amount of inventory in its system, which reduces flow time and increases responsiveness, enabling it to quickly adapt to fluctuations in consumer demand.

Just-In-Time

Just-In-Time (JIT) is the heart of TPS and the main tool used to control the quantity of inventory in the production system. The concept of JIT means deliberately performing an activity just in time for the customer's need, at the last possible moment.. It means producing or transporting only the type of units the customer needs, only at the time needed, and only in the quantity needed. In Toyota's assembly plants, for instance, suppliers deliver most components directly to the assembly plant every two hours, so that there is a maximum of only two hours' worth of inventory in the plant---if a truck is a couple hours late, the assembly line shuts down. Whether the activity is machining a piston, assembling an engine, or delivering engines to the assembly plant, the idea is that by performing the activity as late as possible, the idle work-in-process can be reduced. This in turn reduces flow time and lead time, and improves responsiveness. However, achieving this JIT environment requires flow time reduction, small lot production, level scheduling, flexible and reliable manufacturing processes and suppliers, and proper control systems.

At Boeing, the mindset is not Just-In-Time; rather it can better be described as a combination of Just-In-Case and Just-In-the-Nick-of-Time. "Just-In-Case" refers to the traditional mass production mindset that inventory is an asset and creates a comfortable buffer zone between the manufacturing system and the unpredictable events around it. Fabrication plants build long lead times and idle time into their processes. And the assembly plants schedule parts to arrive weeks before they're needed. In this way, the company is protected from behind-schedule suppliers.

"Just-In-the-Nick-of-Time" refers to the constant expediting that goes on in the company. There are many employees whose job is to chase down late parts and push them through the manufacturing process. Boeing fabrication plants often pride themselves on their ability to respond to emergencies and manufacture a part in 5 or 10% of the normal time. In summary, Boeing parts usually arrive from a warehouse where they have been sitting for weeks or months, or they arrive in an expediter's hands.

JIT is one of the most difficult practices to apply in Boeing, for two primary reasons (1) product complexity, and (2) dispersed supplier network.

Product complexity While a car is composed of about 20,000 parts, a 747 has about 4 million parts, 200 times as complex. In addition, due to the extreme performance, reliability, and safety requirements of modern commercial airplanes, the variety and complexity of manufacturing processes is far greater than that for cars. Add to this the large degree of customer uniqueness of each airplane, and coordinating the production and transportation of so many components becomes a daunting task.

Supplier Network Boeing's supplier network introduces another significant challenge to introducing JIT. As of July 1991, the company worked with about 300 suppliers in 23 foreign countries and 4,000 suppliers in the U.S.[15] One way Toyota improves JIT is by reducing the number of suppliers and requiring them to locate near the assembly plants. Thus, one might argue that Boeing too should rationalize its supplier base, which Boeing might be able to do, but not to the extent Toyota has. It would likely be difficult to locate or develop a small supplier base that could provide for the wide variety of manufacturing processes and technologies required to build an airplane.

Reducing foreign suppliers presents an additional difficulty. Since many airlines are state-owned, governments have significant influence over airlines buying decisions, moving the transaction from a purely economic realm into a political one as well. Governments will often require Boeing to manufacture components in their country as a way to develop technology and to provide jobs. For example, China is building tail fins for 737s as a condition of their purchase of airplanes from Boeing.

Despite these obstacles to JIT, Boeing is starting to experiment with the technique. For example, at the Everett tube shop, where hydraulic lines are manufactured, tube stock is being cut to length at a local supplier and delivered JIT to the tube shop for processing. Once at the shop, the tubes are processed in batches according to the corporate schedule and are delivered to the assembly plant in batches. The shop has developed a new communication systems with the supplier for daily ordering, and costs have been reduced.

Though this is a positive step, it is a sub-optimal one, since the company has set up a JIT relationship with a supplier before Boeing's own internal systems are set up to understand or support JIT. Although tube stock is delivered to the shop JIT, the subsequent processing is still in batches and to schedule---the link between the tube shop and the assembly plant is not JIT. Just as Toyota developed JIT internally and later

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[15] Boeing Chairman Frank Shrontz, quoted in "Boeing News" 7/26/1991.

brought its suppliers on-line, Boeing needs to develop an internal expertise and commitment before bringing in suppliers. If Boeing tries to make its supplier network JIT before its internal operations, the company will find itself with a system it doesn't understand and can't manage effectively.[16]

If coordination is converted to JIT but manufacturing isn't, all that is accomplished is a shifting of the inventory from the assembly plant to the suppliers and fabrication warehouses. A truly JIT supply chain requires the fabrication plants and suppliers to *manufacture* JIT as well, which is a completely different level of this process.

In summary, due to the airplane's complexity and Boeing's dispersed supplier network, it is highly doubtful that JIT here could ever be as finely tuned as at Toyota, but it is a visionary goal and a technique which can still result in significant time and financial savings by reducing unnecessary delays, first inside Boeing, then with its suppliers.

Pull System (Kanban)

JIT coordination requires appropriate communication systems. One that Toyota uses is called "kanban." The word kanban means "visible record," referring to the cards and other signaling devices used to trigger material replenishment. This signal is generated by the user (customer) to request the supplier to build and/or deliver the required material. This characteristic results in the English name "Pull System" because users pull on their suppliers to get parts as needed rather than the suppliers pushing parts to their customers according to a schedule and regardless of need. The concept encompasses both internal (inside the plant) and external (between supplier plant and customer plant) pull signals.

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[16] Such a tendency surfaced several times during discussions of TPS with Boeing personnel who made comments such as, "JIT will work great here if we can get our suppliers to deliver on time."

At Toyota, internal pull signals are used to request that the press room stamp out more sheet metal parts, or that a fork truck bring the next box of parts to the assembly line. External pull signals are used to instruct suppliers to manufacture and deliver parts within a few hours or the next day, depending on how far the supplier is from the customer.

The signals themselves can take many forms: plain or bar-coded paper cards, metal tags, bar coded containers, empty containers, etc. A manufacturer usually has a forecasted production schedule from the customer, but the supplier doesn't actually begin production until a pull signal is received. This reduces the total inventory level of the system by preventing excessive or premature production. The system is quite different from traditional conveyance cards that ride along on a batch of parts "pushed" through system, driven by a schedule.

The benefits of this system are simplicity and flexibility. Rather than having purchasing orders going out all the time with several staff functions tracking the flow of goods and cash, the kanban can serve as both purchase order and invoice. The number of kanbans used gives a count of production. Since every container of parts has its own kanban card, keeping track of the inventory level is simple and automatic. Flexibility comes through the fact that the kanbans specify the production mix.

At Boeing, production and delivery scheduling are determined by a computer system. This computer-driven push system is supplemented by Boeing's form of a "pull" system, expediting. But the idea of a pull system is not new to Boeing: "American producers of military aircraft during World War II tried a pull system after they had to raise output levels drastically in a short period of time and found it difficult to manage the conveyance of components."[17]

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[17] Cusumano, p277.

There are significant opportunities for application of kanban to internal production control of assembly and fabrication operations, but not so much for interfaces with suppliers. The internal control opportunities lie in controlling the flow of parts through fabrication operations, and in pulling components to the assembly line from storage areas or warehouses. One reason kanban isn't very helpful for interfacing to suppliers or fabrication shops is that Toyota's kanban usually triggers actual manufacture of the parts, which may be unreasonable given the complexity and lead time of many airplane components. If kanban were used for these complex parts, it could only trigger shipment, not manufacture. However, there are many simple parts such as hydraulic tubes or subassemblies which can be produced with short lead times and which could be ordered via kanban---and many of these small parts are fabricated in-house.

Even for those parts which can be ordered by kanban, the pace of airplane manufacturing is so steady and predictable that the benefits of pull are less clear here that at Toyota. In Boeing's stable environment, the responsiveness offered by kanban may not be needed---the current computer systems may be sufficient to schedule manufacturing.

Also, because of the high level of customer options, many components are manufactured or purchased for a specific individual airplane, and are already individually tracked by computer. However, on small, high volume parts like standard fasteners which are not airplane-specific, there is an opportunity to use Kanban to simplify the flow of parts from the vendor to the Boeing assembly plants.

In summary, kanban is most appropriate for four situations:

1. Controlling the production flow inside individual fabrication or assembly operations
2. Triggering manufacture of simple components at local suppliers
3. Purchasing off-the-shelf components and supplies from local suppliers

4. Signaling delivery of complex parts which were ordered ahead of time by the computer scheduling system

Production Smoothing

To enable its suppliers to manufacture and supply components just-in-time, Toyota uses "production smoothing" (also called "level scheduling" or "leveling"). The logic is as follows: part of eliminating waste is to prevent accumulating excess resources such as unneeded manpower. Since such excesses are often maintained solely for absorbing variations in demand for the plant's resources, the first improvement step is to reduce such demand fluctuations. In a factory, this means building the same amount of product each hour of each month. When production is not level, then excess resources are needed to absorb the fluctuations. Thus Toyota seeks to build cars at a steady pace. If the production rate is changed, it is done so gradually rather than in a sudden change such as adding or eliminating an entire production shift. Toyota applies leveling to all resources (design, transportation, training, etc.), not just in the factories.

Suppliers also benefit from leveling, a result of the small JIT deliveries made every few hours. With JIT, a supplier that produces ten different parts will produce all ten several different times during the day. A mass producer, on the other hand, orders huge batches of parts from suppliers, requiring the supplier to run the same part for days at a time before changing to the next part. When the supplier is in the middle of a low labor-content part, workers will be idle for long periods of time, which is wasteful.

On a macroscopic level, Boeing's large backlog[18] allows it to have a very level production schedule, and the complexity of the systems makes sudden changes in volume difficult to manage. As a result, Boeing's production rate is held stable.

Once the overall production rate is leveled, then the specific jobs within the production schedule can be leveled by how they are sequenced. A specific application of this sequence leveling concept is seen in Toyota's mixed model assembly line. In such an assembly plant Toyota builds several models of cars in mixed sequence (ex. models A, B, and C would be evenly distributed and run in the order A B C B A B C B A B C B . . . .) Mass producers, on the other hand, would likely batch the models and run them as A A A B B B B B B C C C. If model B requires more resources than A or C, then the batch assembly line sequence requires more resources to run the batch of B, then less to run batches of A and C. So the plant either constantly changes the size of its workforce, or it carries extra workers all the time. The mixed assembly line sequence, in contrast, can maintain a constant level of resources. This concept is further developed in the analysis of the wing skin manufacturing process presented in Chapters 3 and 4.

Unfortunately for Boeing, the nature of airplane sales makes level sequencing difficult in its assembly plants. Currently Boeing schedules airplanes to be built in approximately the same sequence as they are sold. Since airplanes are not purchased in a leveled sequence, neither are they built in one. For example, 757 freighters are assembled on the same line as regular 757s. If ten percent of 757 sales were freighters, then the concept of leveling would advocate making every tenth airplane on the line a freighter. Unfortunately, airplane buyers are not that accommodating. When a customer pays one-hundred-million dollars for a group of airplanes and knows delivery will not take place for

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[18] "Backlog" refers to the airplanes that have been ordered by customers but not yet built. As of 1991, the backlog was several years.

several years (due to the backlog), they want to be the next in line for delivery, and will likely want them all as soon as possible---not one airplane at a time over a 6 month period. This problem is not insurmountable, since Boeing could quantify the savings resulting from leveling and it could offer the customer an incentive to allow rescheduling jobs for leveling purposes.

Another potential problem with assembly plant leveling is the learning curve effect, which has a larger impact at Boeing than at Toyota. Industrial Engineers at the Everett assembly plant indicated that special airplanes such as freighters are best run in batches, since learning curve benefits are then experienced. If the freighters were spread out, then workers would see one infrequently, and the learning curve effect would not occur. This leveling-versus-learning-curve tradeoff was not investigated, and might be a suitable follow-up thesis.

Small Lots

Because of its limited capital after W.W.II, small market volumes, and consumer demand for high variety, Toyota could not afford enough equipment to operate in the large batch, high inventory mode of Ford and GM.[19] Toyota adopted small lot production to reduce inventories and to increase the variety of products which could be run on their limited number of machines.[20] Mass producers, however, with their wealth of capital, have typically used dedicated machines and produced in large lots. The ultimate goal of small lot production efforts is a lot size of one for all processes, which is called "1-piece flow." Today, Toyota keeps only about two hours worth of inventory in its assembly plants, and the parts are usually manufactured in these same small quantities. The result is

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[19] Cusumano, p271.
[20] Cusumano, p285.

reduced inventory and associated savings: less warehouse space, less obsolescence, less tracking effort, etc.

At Boeing, there are so many different parts required for each airplane (for example, the 747 airframe alone has 60,000 different parts) that manufacturing in small lots is ideal. And, in fact, Boeing does manufactures in small lots---small, that is, by automotive standards. But they are sometimes quite large with respect to final assembly rates.

The actual production lot size varies throughout the company, generally getting larger as you move back from the assembly plant into the supply chain. Many components are one-of-a-kind, such as wire harnesses, but others which are the same for every airplane are sized by EOQ (Economic Order Quantity) formulas developed 30 years ago. These lots run from one to thirty pieces or more, which is small numerically, but considering that production rates are as low as one airplane per week, some lots represent six months' worth of production.

With frequent design changes from Boeing engineering resulting in obsolescence, and the appreciable cost of carrying billions of dollars of inventory, smaller lots could save Boeing significant amounts of money. But reducing lot size will be difficult to attain without other significant changes such as setup reduction and improved shop flow control.

Quick Setup

Manufacturing in small lots requires a flexible manufacturing system which is able to adapt to changes in product type, mix, and volume. One source of such flexibility is reducing setup time, the amount of time required to change a process from one activity to another. Toyota seeks to reduce all setup times to zero, so that a process can instantaneously change from making one type of part to making another. Instantaneous setup is an ideal, whereas the more pragmatic goal is to reduce changeover time so that it is no longer a restriction in meeting the small-lot requirements of the customer.

Mass producers have typically considered machine setup an activity to be tolerated or avoided, not one to be improved. Boeing too has considered setup time as a cost of doing business, and has put little effort into reducing it, though there is increasing interest and some recent successes. In one Boeing shop, for example, machine setup was reduced from a range of 17 to 35 hours down to just 8 hours just by using a well-coordinated team of people rather than one person as in the past---there were no changes made to the equipment. And in the Wichita lot-time subassembly shop, better worker coordination and cellular layout have greatly increased productivity by allowing mechanics to quickly change from one job to another.

Boeing can greatly benefit from setup reduction efforts, especially in the fabrication shops; but significantly reducing lot size will be much harder to attain. Smaller lots require other system changes in addition to setup time reduction, such as improved transportation, material tracking, etc. Therefore, Boeing should pursue quick setup as a way to reduce idle time and flow time first, before reducing lot size. "Reducing the setup times of many machines would be one of the easiest ways to introduce the Toyota production system."[21]

Flexible Workforce

As part of its waste elimination strategy, Toyota varies (flexes) the number of workers in response to changes in market demand. For instance, if demand drops by 20%, then only 80% of the workers are used, and the assembly line is run at 80% speed.

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[21] Yasuhiro Monden,Toyota Production System (USA: Industrial Engineering and Management Press, 1983) p84.

Toyota's viewpoint is that if all the workers were on the line, then 20% of their time would be wasted as idleness, which cannot be tolerated.

When there is less work to do, Toyota's unneeded workers are reallocated to other productive activities such as cleaning the plant, performing machine maintenance, training, working at a supplier, or selling cars door-to-door. These reallocations are based on weekly or daily changes in demand. Mass producers, in contrast, generally hire and fire workers to meet changes in demand. And when there is a short-term drop in demand, workers are often kept busy with such wasteful activities as building excess product or shuffling inventory around.

Boeing experiences very little short term variation in market demand, so there is little need to vary the number of workers on a daily or weekly basis. Boeing's variations are usually long term and precipitated by the global economy. These long-term swings are so much larger than what Toyota experiences, that Toyota's methods may not be able to accommodate so many displaced workers. In the extreme case that Boeing could reduce its flow time to a couple months and work off its backlog, then such a flexible workforce might be useful---but it seems doubtful that such flexibility is or should be Boeing's goal.

The union labor contract would likely be a major obstacle to implementing such a flexibility into the workforce. Also, many of the activities into which Toyota puts its excess workers would not be available to Boeing, such as selling door-to-door, or working at a partially-owned supplier plant. These complications further lessen the appropriateness of the technique for Boeing.

Multi-Function Worker

In order to achieve the workforce flexibility described above, Toyota requires multi-function workers. That is, before the number of workers can be easily varied, each worker must know how to do several tasks (functions). In its assembly operations, Toyota organizes workers into teams and assigns each team a work package. This package of work is divided up among the team members, but each member must know all the jobs, and the team members typically rotate jobs every hour or so. As a result, they can quickly redistribute the work package among a different number of workers in response to production rate adjustments.

In Toyota's machining operations, each worker is trained to operate several machines. Simple automation devices enable this multi-function worker to run these several machines simultaneously. As in an assembly team, the workers in a machining cell rotate jobs and can adjust workloads in response to changes in customer demand.

In Boeing, this type of rotation is generally not done. In some areas, such as assembly, it is possible but not pursued as a goal. In other areas, such as fabrication, jobs are specialized with different pay rates, and the union contract currently prevents worker rotation. As a result, there is little incentive to cross-train these workers. If union restriction could be overcome, cross-training would reduce the level of specialization in the workforce, making it more flexible. Because of Boeing's stable production schedule, multi-function workers should be viewed as a source of improved process flexibility rather than short term production rate flexibility.

Machine Layout

Toyota considers equipment layout to be a major influence on a plant's efficiency. Layout is tightly linked with other TPS practices such as worker flexibility, kanban, visual control, etc. To enable workforce flexibility and best use multi-function workers, the "U-shaped" cell is often used (Fig. 2.1). Such a machine layout facilitates varying the number of workers in response to varying demand, because the layout allows easy redistribution of tasks among the varied number of workers. It also facilitates communication as the workers are in close proximity to one another.

Layout also significantly affects a process' required flow time and inventory level. If the machines are located together in a small area with a simple linear flow, then parts can flow through easily and quickly. If, however, the process flow is long or convoluted, extra idle inventory develops and flow time is increased, sometimes by an order of magnitude.

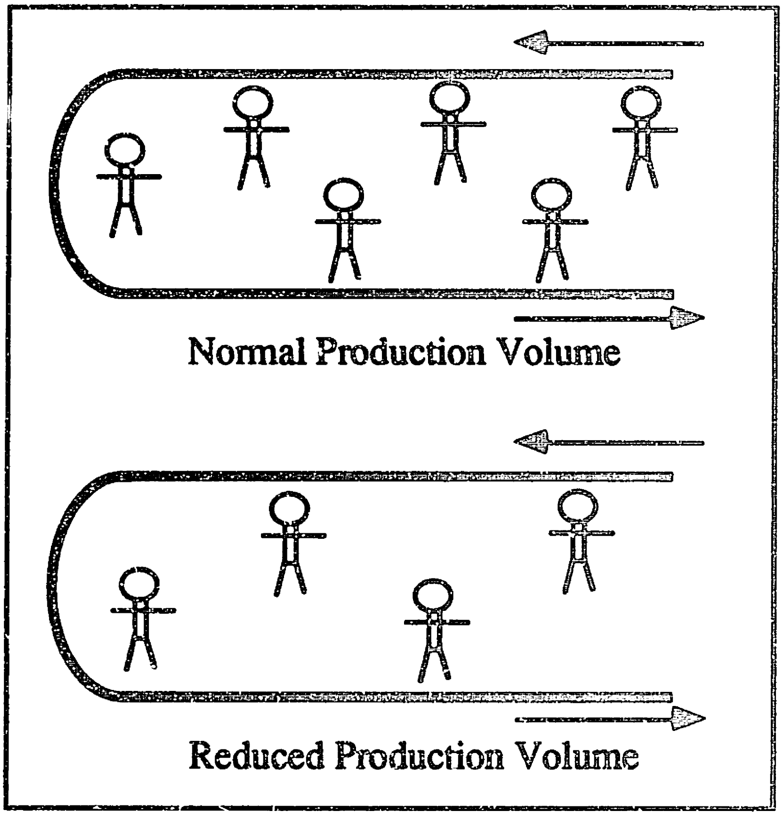

Figure 2.1 U-shaped work area

In the past five years, Boeing has begun to realize the benefits of flow simplification and machine layout. Some of Boeing's factories were built 50 years ago.

Since then, process flows have gradually became more convoluted, and the straight flow of Toyota makes Boeing's knots painfully clear. The new Auburn Sheet Metal Center and Everett Tube Shop were designed to dramatically improve process flow through improved plant layout. The new 777 assembly plant was also laid out to simplify material flow.

All of Boeing's operations can benefit tremendously from better layout, both assembly, and especially fabrication operations. The reduction in redundant material handling alone would be a significant savings.

Quality Assurance

The second main concept of TPS is the idea of "Quality Assurance," which represents a significantly different mindset than the typical mass producer's practice of "quality control." Toyota's quality assurance practices seek to improve the manufacturing process and controls until each process supplies only perfect units to subsequent processes, a philosophy sometimes called "quality at the source." Errors in processes require correction, and all corrective action is a waste of resources. This do-it-right-the-first-time approach to quality extends beyond the factory into every aspect of the business, including design, manufacturing, customer service, etc. Each activity is focused on supplying its customer with the best possible product or service. To prevent defects, Toyota adds "autonomation" to processes to make them mistake-proof, standardizes work activities, employs visual control, and uses inspection to collect data on defects for problem solving activities.

Mass producers, in contrast, focus their quality control activities mainly in the area of 100% inspection and statistical sampling to detect and correct errors. The very name "quality control" speaks of a mindset that there is an acceptable level of defective production, and that the task is to control the actual level of defects to below that target level. Boeing's quality control activities operate very much along these lines, with inspection a key part of the manufacturing process, though Boeing's inspection activity is designed to prevent *any* defects from getting to the customer, for safety reasons. There has been little if any focus on driving out the causes of defects, either in manufacturing or in support activities.

Boeing's current approach to quality focuses on careful product design for performance and extensive, redundant 100% inspection in manufacturing. The company's future may very well depend on its gaining a new perspective of quality that permeates its organization. Senior managers realize this, and in 1986 Chairman Frank Shrontz instituted the CQI (Continuous Quality Improvement) program, in an attempt to begin instilling total-quality thinking throughout the company.

Autonomation

The word "autonomation" comes from the Japanese word *Jidoka*, meaning "Automatic control of defects."[22] It appears to have at least two different meanings and implementations:

1. Mistake-proofing
2. Autonomous control

Mistake proofing refers to designing a machine or process to prevent the production or delivery of a product or service that does not meet customer requirements. This supports production by not allowing defective units to flow to and disrupt a subsequent process, primarily by preventing errors from occurring and then by catching those errors that do

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[22] Monden, p141.

occur. It is implemented through design for assembly, SPC, the ability of operators to stop the line, and other methods.

The concept of mistake-proofing shows how Toyota views its employees. Many companies try to "idiot-proof" processes, to design in excessive guards and safeties so that incompetent workers can't hurt themselves, the equipment, or the product even if they try to do so. Toyota views its workers as intelligent and eager to do a good job when provided the proper environment. As a result, processes are not "idiot-proofed"---they are "mistake proofed," designed with aids to prevent honest mistakes which anyone can make. Examples of mistake proofing, also called "poka-yoke," include designing electrical connectors that can be inserted only the correct way, or machine chucks and fixtures which prevent inserting a part backwards.

Boeing certainly could apply this concept in its operations. Designing assembly cues into the product assembly process would speed up operator training, reduce assembly time, and reduce errors and subsequent rework. This is already done some but could be increased greatly. However, there may be some limitations to the technique. One limitation is the sheer number of parts manufactured and assembled. Merely thinking up ways to prevent every part from being installed backward would be daunting. Also, designing parts so they can only be inserted one way may work fine when parts are just snapped together as in a car, but assembling a airplane is a much more complex process. Also, the variation from one car to another is restricted to a few standard options, but for airplanes it is much more. For example, the passenger cabin floor structure is always unique, because of different lavatory and galley locations. So Boeing seems to lack much of the consistency of operations which allows mistake proofing to work for Toyota.

Mistake proofing processes other than assembly seems more feasible. Common processes such as drilling and riveting can be (and fortunately are) studied to reduce variation. By developing standard methods, variation can be reduced and rework with it.

Autonomous control Autonomation can also mean "autonomous control" which is the addition of machine features to intelligently start and stop the process and to generate signals to summon operator help when needed. For example, spot welding machines at NUMMI count the welds made, and then stop and give a visual signal when it's time for the operator to change welding tips. In machining operations, multi-function workers often operate several machines simultaneously. Simple automation devices added to the machines provide automatic feed or part ejection to reduce workload. Rather than automating to replace the operator, this type of automation allows the machine to perform simple tasks while the operator performs complex tasks such as putting parts into the machine. For this reason, autonomation is sometimes called "automation with a human touch." Due to this philosophy, typical automation projects such as robots are used only when they are in harmony with the people and process involved.

Another example from NUMMI is how windshields are installed. A person places the windshield in a fixture, then a robot applies the sealant, then a simple device lifts the windshield and holds it near the car, then two workers grab it with suction cups and position it on the car. Workers perform the delicate positioning tasks which are difficult to automate, while machines do the easily automated tasks. Compare this to General Motors' Buick City plant where a totally automated windshield cell was installed, including robots to position the glass on the car. This was far more difficult and expensive to accomplish, because in an attempt to eliminate workers, the company gambled on unproved machine-vision technology.

At Toyota, many manufacturing machines are dedicated to a specific part, such as the door welder mentioned above. In this case, counting the welds is easily correlated to weld tip life. At Boeing, however, few processes are repetitive enough for dedicated machines or such focused autonomous control. But it could be used on general purpose machines to monitor the overall process, such as to light a beacon when a machining program is done, or to monitor the condition of cutting fluid. Or, for example, in chemical tank processes a timer could be set up to remove parts automatically, requiring just a simple circuit to engage the crane's lift motor. The operator could insert the parts, leave the crane in place, set the timer and leave.

Visual Control

Toyota believes in an environment of open communication to achieve control, assist autonomation, and enhance learning. In addition to normal written and verbal communication, information is communicated through lights, music, enunciator boards, and posters displayed everywhere. Equipment and inventory are kept visible, and everything is labeled. Visual control supports the assembly process with color-coded parts (for example, similarly shaped left- and right-hand parts are different colors) and active displays (for example, a light comes on when the torque gun reaches full torque). The assembly process is also supported by posted information such as job instructions. The "manifest" is a large piece of paper attached to the car; marked with easily memorized codes, it tells the operator what optional part to put on the car.

Equipment maintenance is also assisted by visual control. For example, air pressure gages are oriented so that at correct pressure the needle is oriented between ten and two o'clock---no special markings or posting is then needed.

Boeing could certainly benefit from visual shop control, such as the simple machine monitoring tricks like the air gages. Boeing could also benefit from visual process control. For example, hand tools such as rivet guns or hi-lock drivers could have sensors to turn on a light when proper force or torque has been attained. By testing the tools periodically, this visual process verification could reduce the need for part inspection and rework. The immediate feedback would also alert workers of quality problems without the typical feedback delay.

Standard Work

Standard work is a tool that achieves consistency in worker production methods. It has three elements: standard operations, standard timing, and standard work-in-process (WIP). Standard operations refers to a fixed sequence of steps which must be executed to perform the task; they are carefully planned and rigidly adhered to. Standard timing refers to the I.E. time study which specifies the amount of time allowed for each step in the standard operations. Standard work-in-process refers to the amount of materials allowed at the station; it prevents over production in fabrication operations. Workers are allowed to modify these work standards but only after proving quantitatively that the change is an improvement and only when the whole work team agrees to the change. Rigid work standards are motivated not by a lack of trust in employees, but by the belief that they improve quality by reducing process variation, as well as the belief that improvement comes only after standardization. In addition to step-by-step job instructions, standard work includes other duties, such as preventive maintenance and housekeeping. Generally speaking, Toyota's standard work is tailored for the repetitive nature of high-volume production. All three elements have varying degrees and places of applicability for Boeing.

Assembly plants Standard operations are certainly applicable and are generally used already due to strict safety requirements, but they differ from Toyota's. Standard timing is not applicable in the way Toyota uses it, due to job complexity and learning curve. Standard WIP isn't an issue in assembly; since the line is rigidly paced, processes are not able to work ahead of schedule.

Most assembly plant tasks are too variable or too complex for detailed standard work. Assembly plant workers perform many different tasks and usually don't repeat the same task until several days later. Instructions do exist for the jobs performed by these workers, but the instructions are lengthy and often specific to a particular airplane, requiring frequent reference to blueprints. Thus, the highly detailed standard operations of Toyota become impractical. However, Boeing's operations would benefit from standardizing and improving common procedures such as housekeeping, handling parts and getting blueprints.

Some assembly operations are repetitive and could be more tightly controlled. For example, the passenger windows are usually installed all at once. On the 767, this takes one person less than one shift. The windows are installed one at a time, working from one end of the airplane to the other, so this repetitive process could be studied and standardized.

Fabrication plants The applicability of standard work in fabrication is quite different from assembly, and there is considerable applicability among fabrication plants. In all shops, it could be used to remind and inform about general job duties such as housekeeping, inventory control, etc.

In some fabrication plants, workers are always doing something different, running hundreds of different parts. They have no regular cycles, no regular sequence of operations. Thus, creating step-by-step instructions would be impractically time-consuming or even impossible. However, as in the assembly plant, standardized procedures for common tasks would be helpful. And as in the window installation example given above, standardized work could be developed for repetitive or frequently-performed operations. This is being done in the Everett lot-time shop, where job instructions are being developed by the workers. For the first time, this shop has documents recording their procedures: which tools are used, how they're used, what quality concerns to watch out for, etc. This database will be of tremendous value as it develops.[23]

In other fabrication shops, such as the skin and spar shop or the tube shop, each component gets basically the same treatment. Here, generic instructions for each process would be helpful. They could detail how to use equipment, what quality issues to watch for, what troubleshooting methods to use, etc.

Inspection

Despite what one may hear about Japanese manufacturing being so good that inspection is not needed, Toyota relies on it as a primary means of achieving quality. Whereas mass producers typically use inspection to catch and fix an expected and acceptable number of defects produced by the manufacturing process, Toyota uses inspection to gather defect data for improvement activities. Defects are viewed not as an inevitable result of faulty machines and inattentive workers, but rather as the result of honest mistakes which any well-intentioned person can make, or of processes being out of control. Data on defects is fed back to engineering and to the production employees who initiate efforts to prevent the same defects from recurring. Rather than chastising workers for defects, efforts are made to eliminate the root causes. This effort often results in

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[23] I encountered a peculiar resistance to standardized work at one Boeing shop. A worker expressed concern that documenting job content would make it easier for management to perform the jobs during a strike. Boeing typically puts its salaried employees to work running machines during a strike. This incentive to keep process knowledge and information from management must be overcome if jobs are to be documented and standardized.

training, changes in standardized work, additional process sensors, or product design changes.

The types of inspection Toyota uses are generally in-process and final inspection. Most receiving inspection is eliminated, and vendors are expected to provide only 100% good parts. Also, production workers are expected to check the quality of parts they produce or use---the inspection task is not delegated solely to the QC department as it is in many mass producers.

At Boeing, inspection is common and of the mass-production type. Incoming materials and components are all inspected. Components and assemblies are inspected at every stage of the manufacturing process: every dimension is measured, every fastener checked. When a defect is found, it is documented, corrective action is ordered, and it is inspected again after the corrective action has been taken. This vast amount of effort requires a large staff of inspectors, trained to detect slight discrepancies. The expense to Boeing of maintaining this vast empire of inspectors, repair people, etc. is staggering, and idle time scheduled for inspection adds significantly to the manufacturing lead time.

Toyota's approach to inspection is a mindset from which Boeing can greatly benefit in all of its operations. If workers could be trained to take responsibility for quality, and the QC group trained and given a new role as problem solvers, Boeing could significantly reduce the cost of quality in its manufacturing operations. There is some evidence that such a transformation is indeed underway.

Boeing's QC organization was recently renamed Quality Assurance. The name change embodies the difference in mindset. Quality "Control" implies there will always be a problem, and that the QC group tries to keep it below some target. But Quality "Assurance" implies that quality can be 100% guaranteed, and that the organization is working toward that goal.

In addition to its symbolic name change, the group's role is changing in some plants. For instance, in the Everett lot-time shop, where small detail parts are assembled into units for later assembly into the airplane, workers are being trained to inspect their own work. After completing the training program, workers must prove their work is defect-free for a period of time before being authorized for self-inspection. QA does not perform 100% inspection of work done by those workers who have passed the certification, though there are occasional random-sample inspections to make sure the certified workers aren't slipping. According to their supervisor, this program has resulted in more employee ownership of their work, as well as the elimination of inspection efforts. The workers also have formed problem-solving teams, which are working to identify the root causes of its most persistent problems.

In the assembly plant, engineers and workers have been using a new system that allows workers to inspect the holes they drill in sheet metal parts. The new measuring system's accuracy is an order of magnitude better than the inspection method previously used, enabling meaningful SPC data collection. After months of effort, quality is significantly higher, rework is down, operators inspect their own work with the system, and QA inspectors are used only for occasional audits.

In more than one plant, there are plans and efforts to totally eliminate 100% inspection. It seems operator self-inspection is becoming a popular idea at Boeing. This emerging pattern of self-inspection is different than Toyota's program, for Toyota still routinely uses 100% inspection as a last-ditch effort to prevent defects from getting to the customer, as well as for data collection. Employee-inspection has many advocates inside and outside of Boeing: it eliminates the overhead cost of inspectors, reduces flow time, tightens the quality feedback loop, etc. But it also removes the very people whose years of inspection experience could be used for defect data analysis and root cause analysis.

Self inspection will likely have a practical limit at Boeing, for the Federal Aviation Administration (FAA) carefully monitors and controls the manufacturing, inspection and certification practices at domestic aircraft manufacturers. The FAA has been involved in the new inspection process at the lot-time shop and are carefully monitoring this new role for QA. Such FAA involvement needs to continue as Boeing further develops self-inspection practices. Because of the complexity of large airplanes and the overriding concern for safety, final inspection will likely never be eliminated---but Boeing can certainly gain a great deal by eliminating intermediate and incoming inspection steps. Reducing in-process inspection will require improvements in the reliability and accuracy of manufacturing processes and vendors, which certainly are achievable.

Boeing's QA and manufacturing organizations are just beginning to develop the new type of relationship described above. As it continues to develop, the current role of the QA department will be significantly changed and its size reduced. There will likely be resistance to this as QC was a powerful organization in the company. To lessen the impact of this resistance, Boeing management should lead QA to assume a new role of training workers in SPC and other techniques, to be quality teachers and coaches, rather than overseers.

To illustrate the benefits of Toyota's QA approach, here is an example from NUMMI. The plant does not have a single in-process check of the vehicle's electrical system. The wiring harness and other electrical components are all installed in the vehicle, and the inspectors visually verify that the correct connections are made, but the system is not tested electrically until the car is completely assembled and the engine is started to drive it off the assembly line. By contrast, in a typical US auto plant there may be several intermediate checks of the various wiring harnesses and electrical systems during assembly: the door electrics, the dashboard system, the engine system, and integrated body system before engine installation, and finally the whole vehicle system. This is all before the car leaves the assembly line. Now each one of these tests requires operators, equipment, programming, assembly line space, power, maintenance, etc. The total cost of inspection is significant. Rather than spend its money on testing, Toyota spends money on improving the electrical system's design, the quality of connectors, and the assembly process. As a result, the electrical system is so reliable that no electrical checks are needed.

Now if Boeing were to look at total system costs in a similar fashion, and allocate more effort and money to improving the reliability of the manufacturing and assembly processes, the need for and cost of inspection could be reduced, with an additional benefit of reducing rework, flow time, and inventory. A major difficulty in achieving this goal is that manufacturing processes must be understood and quantified in great detail before they can be brought into such tight control to allow inspection-free processing. This level of understanding requires significant time and allocation of factory floor engineering and workforce training. In fact, Boeing would have to do far more process study than does Toyota, owing to the wide array of processes and high complexity inherent in the aerospace business.

Respect for Humanity

The third main goal of TPS is "Respect for Humanity." Toyota believes human resources must be fully utilized for the company to attain its cost objectives. While at times this appears to mean making the employees work harder, it also engenders respect of workers by management, resulting in egalitarian treatment among workers, training, job rotation, and ownership of manufacturing processes by the workforce. Workers are viewed as a vital resource, not a variable cost. Another aspect of respect-for-humanity is a paternalism which includes lifetime employment, and company loyalty.

Toyota considers employee motivation for continuous improvement to be a primary means for gaining an edge in the marketplace. Standardized improvement activities formalize the involvement for factory workers.

Creative Thinking

All workers have good ideas to contribute to the company and the performance of their jobs. Toyota workers are encouraged to share these ideas, and superiors provide a ready ear. This attitude comes from their philosophy of "keizen," the elimination of waste through continuous improvement, which is most effective when all employees are involved.

Improvement Activities

Believing that all workers have valuable input to offer, Toyota has developed a forum for soliciting their input and a methodology for evaluating that input. The forum for continuous improvement is the work team and its group-based suggestion system. The evaluation methodology is a process to gain approval from the whole team and then standardize the ideas' implementation.

As team members learn and rotate through the several jobs in their team, they will have ideas of how the jobs can be improved. Because of the rigid adherence to standard operations (part of standardized work), operators cannot implement their ideas unless the standard work procedures and documentation are changed. And since team members rotate through all jobs, every member must approve it, as well as the team leader. And since both shifts do the same standard work, both teams must approve it. Therefore, suggestions are shared with the team for discussion, time study, and possible approval.

Toyota encourages workers to continually seek small improvements rather than the "silver bullets" after which Americans typically strive. The result of this system is that worker morale is improved by getting everyone involved in the drive to eliminate waste. And because of their sense of job security, workers are willing to pursue improvements that will eliminate their own job, confident that they will then get a better job.

In addition to improvements of their own jobs, work teams are also involved in problem solving to address specific quality or process problems discovered by inspectors. Though functional experts may be brought in for particularly onerous problems, the team is usually relied upon to solve them. Workers are trained in skills necessary for the type of problem-solving which is delegated to functional specialists in other companies. For example, at NUMMI all workers are trained in the basics of time and motion study, usually the domain of the Industrial Engineering department.

When Toyota inspectors find a defect, the information is immediately fed back to the work team, and efforts are begun to determine its cause and to prevent it from recurring. This type of improvement leads to an interesting paradox concerning how defects are viewed. On the one hand, many efforts are expended to eliminate defects by improving the manufacturing processes, yet on the other hand a defect is also seen as a treasure, for it provides information on which teams can pursue further process improvement.

When applied to Boeing, this worker organization and involvement are very attractive. Most of Boeing's workers are highly experienced, and their knowledge is a largely untapped resource. At Boeing, increasing numbers of workers are being organized into "CQI" (Continuous Quality Improvement) teams for organized problem solving. CQI teams offer a forum that encourages involvement from which Boeing will greatly benefit.

Before the teams can be effective, however, workers need an increased sense of their role in the total manufacturing endeavor. Boeing usually relies on specialists for process improvements and for chasing down quality problems, such as the engineering department which is very involved in resolving major QC problems. Due to this focus on specialists for process improvements, worker input is often not sought or welcome. Some of this may come from legitimate reasons such as the complex nature of many problems, or FAA regulation on who can approve deviations from the standard process plan.

Management Systems

A critical supporting and driving mechanism of TPS is the policy-setting management teams which promote company-wide quality control and cost management. These teams monitor the implementation and evolution of the various TPS concepts and the systems which support them. They ensure consistency and constancy of purpose and procedure.

Because this issue gets at the heart of a company's management structure and culture, it is difficult to access its applicability to Boeing. I can, however, observe that the many departments and organizations within Boeing's corporate structure show sub-optimization, sometimes to an extreme. And some organizations seem to be working at odds with one another.[24] The company could benefit from more coordination in setting manufacturing strategy and policy.

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[24] In several plants I heard complaints from managers and engineers that a particular R&D organization would develop machines and processes for which the plants hadn't asked and had no need. I also observed situations where engineers in the assembly plant had never talked to anyone in the fabrication plant where their parts are made.

A particular area where top-down coordination could better encourage TPS-type ideas and activities is the company's performance measurement system. Current measurements are mainly labor-hour based with such adverse effects as job insecurity, and automation and machine purchase decisions being based on labor savings rather than total cost or fit with manufacturing strategy. When creating new metrics and incentives, management must be watchful for conflicting goals.[25]

OPERATION-SPECIFIC TPS APPLICABILITY

So far this chapter has addressed the general applicability of various TPS concepts. The preceding general discussion often mentions how a particular TPS concept varies in applicability due to the particular characteristics of different plants, such as fabrication versus assembly. This section of the chapter addresses that applicability variation.

Each Boeing plant has unique characteristics which suggest differing degrees of TPS applicability and differing approaches to implementation. For several types of plants, operational characteristics are described, as well as their constraints, feasible changes, improvement potential, and obstacles to be overcome. The discussion is in aggregate terms, not nearly as detailed as the skin and spar shop study presented in the next chapter. The types of plants studied are as follows:

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[25] One small fabrication shop had a performance management system where each manager set personal goals in support of stated corporate goals. The inventory manager set a goal of 99% inventory accuracy, and the production manager set a goal of moving the small-parts inventory from the store room to the plant floor to improve flow time, turn rates, and visual control. A conflict arose because moving the inventory reduced kitting time, manpower needs and flow time, but it also reduced inventory accuracy, since the parts were not as rigidly monitored as when they were in the store room.

- Fabrication
    - Job-shop fabrication, including sub-assembly
    - Flow fabrication

- Final assembly

- Suppliers

Figure 2.2 illustrates how these operations fit into the company structure and flow of materials.

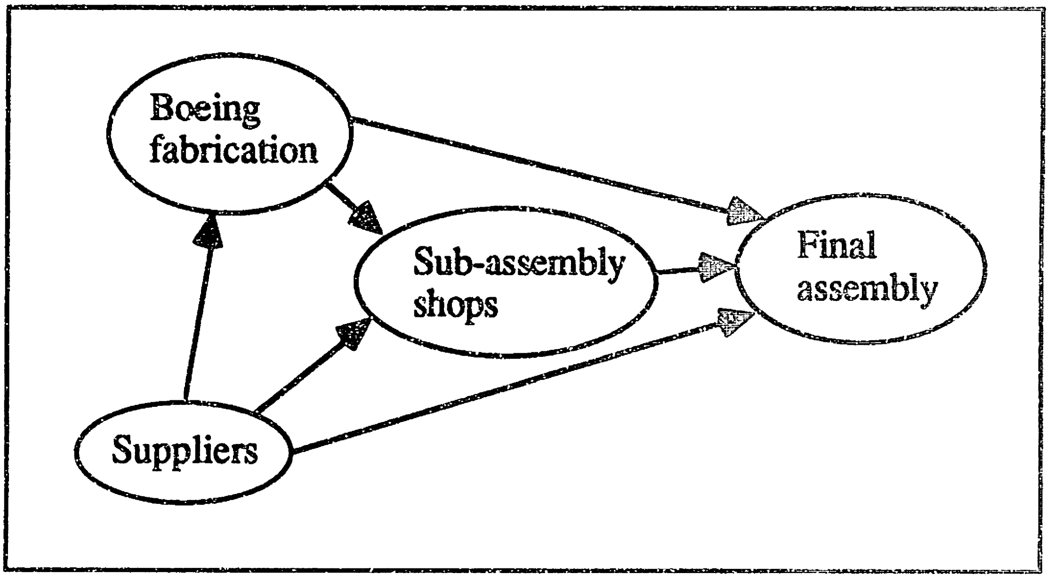

Figure 2.2 Manufacturing organization and flow of materials

TPS Applicability to Fabrication

Boeing has several fabrication operations producing tens of thousands of different components, ranging from simple brackets and tubes to complex wire harnesses and huge wing skin panels. These fabrication facilities demonstrate Boeing's wide array of process technologies. And it is here that the most waste can be observed: large production lots, poor equipment reliability, stifling inventory levels and long lead times. The final assembly schedule is sacred at Boeing, and fabrication is managed to guarantee timely delivery to the assembly plant. Therefore, fabrication lead times are long, on the order of two years for some components. The general benefits of TPS applied to fabrication are improved process reliability and responsiveness, leading to reduced inventory and flow time, which in turn reduces lead time and cost. Fabrication is addressed first for three reasons:

1. It is at the beginning of the supply chain, and improvements there can have multiplied benefits in later stages of the total manufacturing system.
2. It is part of an internal supply chain, and TPS process improvement efforts should begin internally.
3. Process experimentation here is less risky than in the assembly operations, because component finished-goods inventory can buffer the fabricator in case there is a problem with the implementation.

The following fabrication shops are divided into two groups for this discussion: job-shop and flow-shop.

Job-Shop Fabrication

Job-shop fabricators are those with a high variety of products and little consistency in process plans, such as the Auburn Sheet Metal Center and Machine Shop. It also includes to a lesser degree some sub-assembly shops such as lot-time, which assembles a huge variety of small units which are later installed in the final assembly plant. The basic improvement strategy in these shops is to reduce setup time and lot size, then simplify operations by organizing the shop into cells, each of which manufactures a group of similar components. This cellular approach reduces handling, improves communication between workers, and simplifies production control and tracking. These benefits, in turn, reduce flow time and inventory.

Initial improvement efforts should begin with setup time reduction. This reduces flow time and increases available machine capacity, allowing a reduction in lot size. Trying to reduce lot size or flow time before reducing setup time would be a more difficult approach (maybe impossible). A long term plan might look like this (---> means "leads to"): quicker setup ---> less idle time ---> more time available to perform setups ---> more setups ---> reduced lot size ---> less work-in-process ---> shorter flow time. With this approach, gains can be made with the existing plant layout.

For further improvement, the equipment should be reorganized into cells, allocating equipment based on group technology. Then, extending the improvement process presented above gives the following procedure: reduced setup ---> less work-in process ---> more available floor space ---> change to cellular layout ---> smoother flow ---> smaller lots ---> less work-in-process ---> pull system ---> one-piece flow ---> JIT --> reduced need for finished-goods inventory ---> reduced lead time. This cellular approach allows each cell to operate like a flow fabrication process, which is discussed later.

Some fabrication operations may be fundamentally job-shop oriented with too large a variety of processes and products to be broken into cells (tooling fabrication, for example). In this case, improvement efforts should focus on setup reduction, workplace organization, standardized work, etc.

Flow-Type Fabrication

Flow fabrication shops are those in which all the components produced go through the same or similar processing steps, such as the wire shop, tube shop, or the skin and spar shop. Flow fabrication also includes low-variety sub-assembly shops such as Propulsion

Systems Division, which assembles the engine struts and dresses the engines. The basic improvement strategy here is to reduce setup time and lot size, straighten the flow, level the production schedule, more tightly link the processes, and work down the inventory, resulting in reduced flow time. Flow fabrication is Toyota's preferred manufacturing method.

Flow Fabrication Improvement Process

1. Increase machine reliability to reduce unplanned downtime and increase machine availability. Random breakdowns will scuttle JIT, so this must be done first. Preventive and diagnostic maintenance are a must.

2. Reduce setup time to allow the following lot size reduction.

3. Reduce lot size. A low-risk approach is to reduce lot size proportionally to setup time reduction, so that total monthly setup time is held constant. Set a challenging but achievable time-based lot size goal, such as one month's production per lot.

4. While these machine reliability and setup reduction campaigns are proceeding, have Industrial Engineers work with operators to develop standard work for each process. Establish standard times required for each job on each process. Also work to reduce variation in the processing time and effort for each different process and component produced. Excessive processing time variation will interfere with the next step.

5. Use standard work and processing times to balance shop loading and to create a level production schedule, one where variation in demand on the manufacturing resources is minimized.

6. Release work into the shop based on the level schedule. Run the shop like an assembly line, disallowing parts from skipping one another.

7. Establish maximum work-in-process levels between stages in the manufacturing operation. This can be done by limiting the storage areas. It will also require discipline, so workers and managers don't squirrel away extra stock.

8. Gradually reduce the maximum allowed WIP between operations simultaneously with further setup time and lot size reductions.

9. When WIP is sufficiently reduced, begin using kanban for pull linkages.

10. Continue to reduce the lot size in pursuit of one-piece flow.

11. Continue to reduce WIP. Total buffer elimination is the ideal, and can be achieved on production lines where the parts produced are nearly identical. But since most lines run parts with variety, some buffer stock will likely be required. As WIP decreases, processing time variations will have more noticeable impact on actual buffer levels between stations. Eventually some operations will be starved, but that's acceptable as long as it's not the bottleneck operation. Buffer WIP will be highest in front of bottleneck operations.

12. Focus improvement efforts on bottleneck operations to reduce their need for buffer. Efforts include process analysis and CQI team efforts.

13. For the troublesome operations that add much of the variation in processing times, assign manufacturing engineers to work the process variation down.

14. With reduced buffers, variation in processing times may create variations in labor needs. If this occurs, pursue moving workers between operations throughout the day, which will require cross-training. Union resistance on this is quite likely, so approach it carefully. But if the benefits can be seen by all and the workers don't feel threatened, it might work. If only a non-binding shop agreement can be obtained, then maintain contingency plans for reinstating some WIP in case the flexibility is lost in a union disagreement.

TPS Applicability to Assembly Plants

An airplane assembly plant is an overwhelmingly complex operation where million of components are integrated into one of the world's most complex machines. The differences between fabrication and assembly plants provide different applicability opportunities, requiring different approaches to implementation. For example, fabrication shops' basic requirement is to deliver a quality product before a deadline, which gives the fabricator freedom to manufacture parts early and store them, or to source work out, whatever, as long as the part is at the assembly plant when it's due. The assembly plants, however, are strongly schedule driven, with every process and assembly advancing at the same time---there is no chance to build ahead or to catch up later on missed production. Pressures to keep the assembly line moving are immense, and, as a result, there is much trepidation surrounding ideas which might disrupt the line. This risk aversion would likely make it more difficult to experiment in the assembly plant than in the fabrication shops.

In the assembly plant there are several areas in which TPS application will reap benefits as mentioned throughout the general discussion earlier. Inventory reduction is often mistakenly perceived to be the primary benefit of TPS. It is indeed a benefit, but not the only one or even the major one. Inventory reduction, if implemented before reliable control systems are in place to support production, is risky. Inventory reduction efforts are where many companies implementing JIT have failed. Therefore, it must be approached cautiously and systematically. The US automotive assembly plants who have implemented JIT may provide an appropriate implementation model for JIT coordination of Boeing's assembly plant supply chain.

1. Remove inventory from the assembly lines, placing it in storage rooms or a warehouse to which suppliers deliver.

2. Use kanban to pull kits and components from the storage area to the assembly line, which controls the amount of inventory in the plant. An internal pull system like this allows the plant to decouple its internal coordination from the outside world.

3. Improve inter-plant coordination so that Boeing fabrication and sub-assembly facilities respond to the assembly plant kanban and deliver directly to the assembly line, bypassing the warehouse. Complex components could still be manufactured

based on the corporate computer schedule, but the finished kits and components would be delivered to the assembly plant JIT in response to pull signals.

4. Work with outside suppliers to begin making their deliveries directly to the assembly line, bypassing the warehouse.

Suppliers

This topic was purposely put last, for Boeing needs to understand TPS and how implementation impacts their operations before changing supplier selection and coordination practices. The point is not that the supplier interface should be neglected or that it should be improved last---the point is that to simply pressure vendors to deliver JIT is to miss the point of JIT.

In 1991 Boeing had 4,000 U.S. suppliers and 300 foreign suppliers in 23 countries.[26] It is likely that some of these 4,300 suppliers will easily be able to hold back deliveries and reduce Boeing's in-house WIP, but only by holding the WIP in their own warehouse---so there is no real system improvement. Systemic improvement requires that the suppliers perform their own internal JIT improvement efforts to be able to actually manufacture in a timely fashion. If the Boeing purchasing organization is going to reduce inventory of purchased parts, it must be sensitive to which vendors can actually improve their operations as opposed to merely shifting WIP.

Boeing should not pressure vendors to deliver JIT if Boeing's own internal fabrication is not pursuing JIT too. Until the fabrication shops are JIT, Boeing

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[26] Boeing Chairman Frank Shrontz, quoted in Boeing News 7/26/91.

management and the assembly plant may not know how to properly manage a JIT network or how to interact with a JIT supplier.

Summary Matrix

Figure 2.3 summarizes the applicability of TPS methods to Boeing's various operations. The matrix gives more detail and for more shops than were specifically discussed in this chapter. Rather than describe the meaning and logic behind each matrix entry, the general reasoning is presented. A variety of operations was selected to fully cover the spectrum within Boeing, from the simplest shop and product to the most complex. These operations are compared against only the technical aspects of TPS, the items on the lower-left portion of the pyramid presented in Figure 1.1. (The other elements in the pyramid are assumed to be fully applicable with no plant-level distinction.)

Each entry in the matrix is a representation of how applicable a particular TPS concept is to a particular operation. In one sense, all of the entries should be solid dots, because given enough time and effort Boeing could implement TPS just like Toyota[27], but at what cost? To give the chart meaning, considerations other than purely conceptual applicability had to be considered. Think of each entry as representing the mutual fit between concept and operation, not whether TPS can be force-fit to the shop. The ratings assigned to each matrix entry were based on several factors:

1. Appropriateness of the TPS element to the operation: For example quick setup has no connection with purchased parts, and standard work is not very practical for final assembly. But quick setup is a great match with all the fabrication shops.

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[27] Richard Schonberger, a JIT consultant thinks so. He received a copy of this matrix and commented that I had been too conservative in my assessments.

2. External constraints: For example, the union would likely oppose flexible workforce.

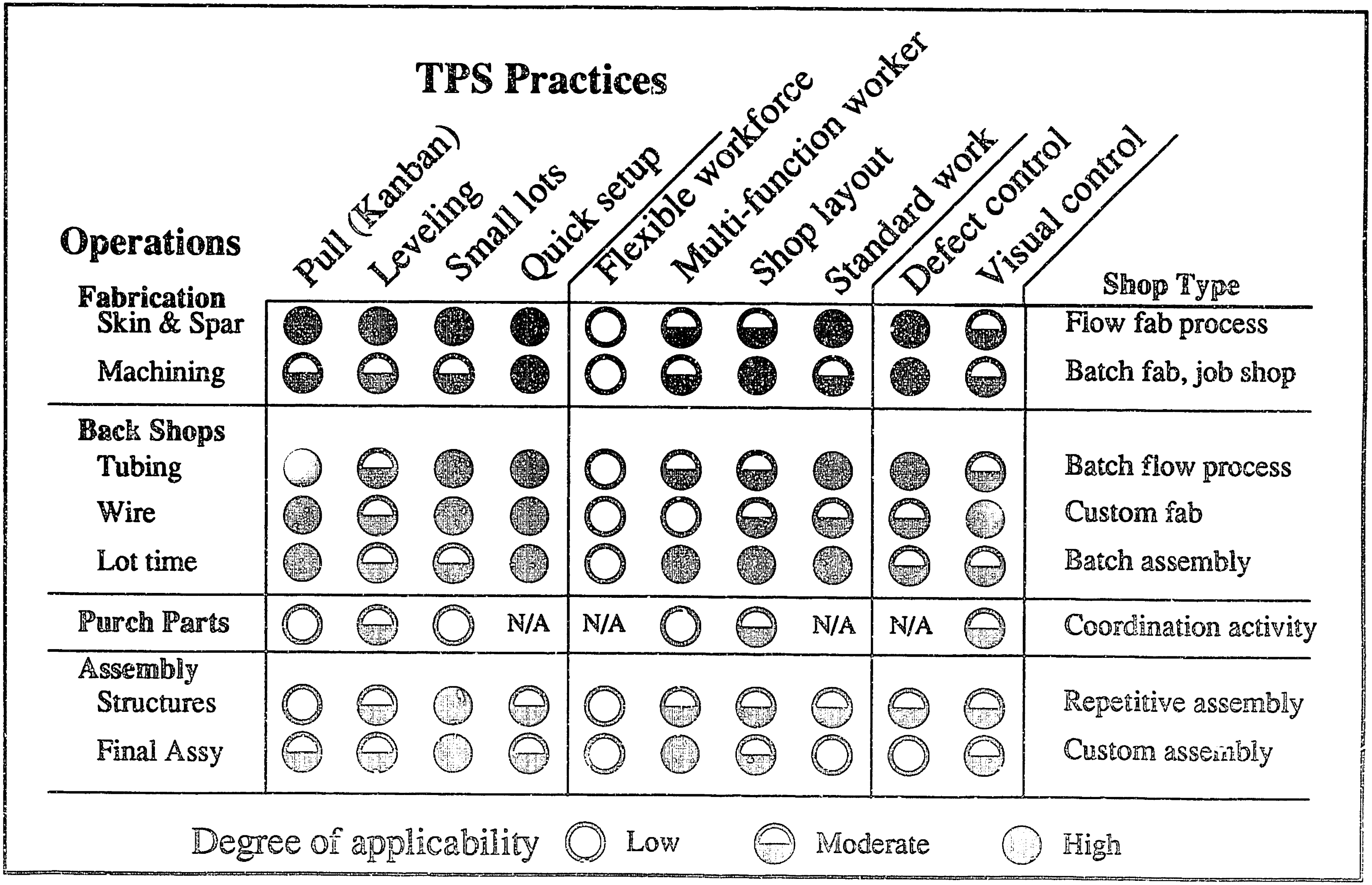
3. Reasonable time frame of 5 years. For example, shop layout can certainly help any plant's flow, but its unlikely the skin and spar shop or assembly plants will rearrange major equipment within the next few years, if ever. The union would likely oppose multi-function workers, too, but they might agree with it after a few years of study and dialogue.

The entries can be used for prioritizing an implementation plan: the solid dots should be worked on first, then the mediums, etc. A "low" entry (hollow dot) means that this item will be difficult to implement or will have little near-term benefit---it doesn't mean the item will never be worth pursuing.

Some of the solid dots represent high-potential opportunities, while others represent an already-existing application. For example, lot time could greatly benefit from better shop layout; therefore, it has high potential. The wire shop, in contrast, already runs small lots, 1-piece flow, because each wire harness is unique, so it has a solid dot due to existing practice. Both are solid dots, but for different reasons.

Based on this chart, the fabrication shops provide a more natural fit for TPS, have more room for improvement and greater potential benefit by application of TPS than does assembly. Notice that the matrix's top row is the skin and spar shop, and that it has one of the best overall fits with TPS. For this reason it is analyzed in detail in Chapters 3 and 4.

The "flexible workforce" column merits explanation. Flexible workforce refers to the company's ability to vary the number of workers in response to varying market demand. As discussed earlier, Boeing's business cycles are stable on a monthly basis, so Toyota's type of short-term work-force flexing is not applicable. When Boeing does have



Operations	Pull (Kanban)	Leveling	Small lots	Quick setup	Flexible workforce	Multi-function worker	Shop layout	Standard work	Defect control	Visual control	Shop Type
Fabrication											
Skin & Spar	●	●	●	●	○	◒	◒	●	●	◒	Flow fab process
Machining	◒	◒	◒	●	○	◒	●	◒	●	◒	Batch fab, job shop
Back Shops											
Tubing	●	◒	●	●	○	◒	◒	●	●	◒	Batch flow process
Wire	●	◒	●	●	○	○	◒	◒	◒	●	Custom fab
Lot time	●	◒	◒	●	○	●	●	●	◒	◒	Batch assembly
Purch Parts	○	◒	○	N/A	N/A	○	◒	N/A	N/A	◒	Coordination activity
Assembly											
Structures	○	◒	●	◒	○	◒	◒	◒	◒	◒	Repetitive assembly
Final Assy	◒	◒	●	◒	○	●	◒	○	○	◒	Custom assembly

Degree of applicability ○ Low ◒ Moderate ● High

Figure 2.3 TPS applicability matrix

a downturn, it is usually so severe that there are thousands of idle workers, likely more than could be absorbed by Toyota's flexing methods.

CONCLUSIONS

JIT and the other TPS practices have given Toyota a degree of responsiveness that is beyond most mass producers. Thus, Toyota and its suppliers can quickly respond to changes in customer demand. After studying the Boeing company and the applicability of TPS to Boeing, my conclusions are as follows:

- The high-level TPS concepts of cost reduction, quantity control and quality assurance are certainly applicable to any business.

- For most TPS concepts, the degree of applicability varies between plants. Vertical slices through the applicability matrix (Fig. 2.3) illustrate this point. For some TPS concepts, such as quick setup and standard work, applicability is clearly differentiated between assembly and fabrication operations. Thus, different plants will require different implementation plans. The differences are in details and priorities, not in vision.

- All of the TPS concepts are applicable to Boeing's operations, but some concepts are more applicable than others for an individual shop and for the company as a whole, a result of the airplane industry's nature and of the business environment. Horizontal slices through the applicability matrix illustrate this point. For example, quick setup is highly applicable considering the high variety in fabrication and the complexity of setup in assembly; but flexible workforce is not very applicable given the long industry cycles. There is also a difference in the implementation time frame: quick setup could be implemented in a year, but a corporate pull system would take several years to develop.

- Due to differences between the two companies, most TPS implementations at Boeing will be of a different form than at Toyota. For example, kanban in a Toyota shop often includes dedicated, custom, reusable transportation and shipping containers and kanban marker cards. But with the vast number of different parts made by Boeing fabrication, it would likely be impractical [illegible] use dedicated containers. Thus, Boeing's unique business requires thoughtful implementation of TPS, not merely copying the techniques.

- Current performance metrics do not encourage TPS ideas.

- CQI (Continuous Quality Improvement) teams are a useful tool for involving workers in the transformation.

- TPS factory control techniques can help build a mindset of continuous improvement and provide a common set of tools for all shops and workers.

Most Fruitful Areas for TPS Implementation

A major debate throughout this thesis project has been whether TPS improvement efforts should begin in the fabrication shops or in assembly. The issue begs the question, what type of operation can most benefit from TPS practices? Some JIT consultants admonish all companies to adopt the concepts in all aspects of their operations, but that is simplistic. Although TPS methods are widely applicable on a conceptual level, TPS was clearly developed for medium to large scale repetitive manufacturing, and that is where the methods shine. Thus, within Boeing, the areas most amenable to and likely to benefit from TPS are those which repetitively produce a standardized product and where production can be leveled, which leads to two additional conclusions:

- TPS is more applicable to Boeing's fabrication operations than to final assembly.

- Among the fabrication shops, TPS is more applicable to flow shops than to job shops.

In addition to the question of what shops have processes and products most amenable to TPS, consideration should be given to which shops are most likely to succeed in the transformation and in which the benefit will be most significant. I believe the fabrication operations have the greatest potential for improvement in the near term.

Another issue to consider is in which shop should Boeing begin its learning about TPS? Self-contained shops (ones which control the stock every step from raw material to finished goods) such as skin and spar or tube shop may be where learning should occur first. For such shops have the freedom to experiment with material flow and scheduling more than other shops.

Also, if the goal is to have all of Boeing's plants operating in a more tightly coordinated fashion, approaching JIT, then it may be the best approach to begin at the bottom of the supply chain and improve responsiveness there before supplying the assembly JIT. If JIT is started in the assembly plant first and it tries to pull parts from the fabrication shops, they won't be responsive enough to supply JIT. Note that Taiichi Ohno began his development of JIT in a machining plant, not in the assembly plant.[28]

RECOMMENDATIONS

In addition to the detailed implementation plans presented in the middle of this chapter, here are some general recommendations on how to approach instilling TPS-type thinking onto the company.

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[28] Cusumano, p278.

- Look inside. There are interested, knowledgeable employees within the company. I met several who were somewhat knowledgeable and eager to learn more and try the concepts.[29]

- Study and learn from other low-volume industries who have implemented TPS concepts: ship building,[30] Japanese aircraft suppliers, locomotive manufacturers, Otis elevator, etc.

- Run a pilot plant experiment and give it high corporate visibility to build credibility for the concepts. Success breeds success, so pick one where success is likely, such as the tube shop.

- Develop new performance measurements which encourage and reward TPS practices such as process control and WIP reduction.

- As in any such endeavor, without top management's backing, one glitch where a fabrication shop shuts down the assembly plant can kill the whole desire to experiment, learn and improve.

- Expect resistance and prepare do deal with it.

Follow-up Research Proposals

This thesis is of a broad scope, and as such was designed to be the launching point for several follow-up projects. Here are some potential projects which became apparent through the course of my work:

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[29] For example, Boeing had a program in 1989-90 called the Total Quality Associate Program, where several employees intensely studied JIT, TQM and other leading production management concepts. They all published papers, and some have been able to experiment a bit with what they learned. Such people should be tapped to lead TPS programs.

[30] James L. Nevins and Daniel E. Whitney, Eds. Concurrent Design of Products and Processes. (New York: McGraw Hill, 1989) p61-65.

1. Setup time reduction is a key element in TPS and one of the first TPS activities advocated by this thesis. A follow up project analyzing setups and suggesting reduction methods could help get some plants started on the efforts. This could be done for processes in the fabrication shops and/or for major jigs in final assembly The project could also compare setups to those used in other similarly low-volume industries as locomotives and ship building.

2. Whereas this thesis focused on a flow shop (skin and spar), a low-volume high-variety job shop should also be studied in detail. The Auburn machine shop is a good candidate, as it is currently investigating quick setup, manufacturing cells, and SPC techniques. One of the Everett back shops (tube, lot time, unit issue, etc.) would also be a good candidate.

3. A repetitive, low-variety assembly operation such as the Propulsion Systems Division in Kent would be a simple way to study the applicability of TPS to Boeing assembly plants in general.

4. Toyota believes a car's quality begins with an accurate body, so the body panels are stamped at the assembly plant. Applying this to Boeing, consider how an assembly plant might operate if the entire body were manufactured on site. How could the capital cost be kept low? Which fabrication shops can be easily replicated at the assembly plant? Which operations should be at the assembly plant to guarantee optimal quality control? This study would be especially interesting if framed in terms of a green field plant located far from Seattle.

5. A project is needed to study pulling components into the assembly plant from fabrication and suppliers. I began developing a pull system for replenishment of standards racks, but wasn't able to complete it.. A project to complete and expand the idea into a more detailed study could also include pulling other parts from fabrication, such as tubing, where fabrication is located just across the street. This project could set up a working trial system.

6. Toyota seems to have different ideas about automation than most US companies. Re-evaluate some of Boeing's past automation projects (both successful and failed) with TPS in mind. Hypothesize how the projects and decisions would be different if based on TPS criteria: would Toyota have done it the same way?

7. The role of CQI in Boeing's improvement efforts could be studied and compared to Toyota's culture and worker participation programs.

CHAPTER 3

WING SKINS WITH TPS

This chapter presents a detailed TPS applicability study of Boeing's wing skin fabrication shop. It describes the current wing skin fabrication process, proposes a new TPS-based management framework and manufacturing process, describes the benefits of the new system, and offers an implementation plan. (Numerical analysis of flow time and inventory level improvements is presented in Chapter 4.) The proposal amounts to a revolution in the shop---a revolution not in machinery or processing technology, but, rather, a revolution in the thinking about this shop and its systems.

The objective of the analysis is not to challenge Boeing's current system, but rather to understand it and then to ask how it might have formed given a different set of manufacturing principles, namely those of Toyota. Applying and extrapolating knowledge of Toyota's automobile manufacturing philosophy and techniques allows one to theorize how Toyota might produce the same component. Phrased another way, "If Toyota manufacturing engineers were given control of this plant, how might they run it?" The analysis considers management and manufacturing engineering issues such as inventory, flow time, and machine maintenance, rather than fundamental design issues such as the choice of materials or manufacturing processes.

Specific shop study

To focus the TPS applicability investigation, the processing of a single component through the entire manufacturing system was studied, from fabrication to final assembly. The objective was to ask how would the process be affected by the full implementation of TPS. After visiting several fabrication shops, the wing skin manufacturing process was selected for detailed investigation, for the following reasons:

1. There appeared to be significant potential for improvement in this shop
2. These components are major elements of the airplane structure
3. Boeing has strategically decided to manufacture these components in-house
4. These are high-cost components, so improvements can have significant financial impact
5. The physical characteristics of the process are amenable to TPS: it is basically a flow process in a self-contained shop, with little variation in the process plan

Analytical Process

The method by which the wing skin manufacturing process was analyzed is presented below, though it is in a slightly different order than how the findings are presented in this thesis:

1. Document the current manufacturing process for a wing skin panel, from raw material, through fabrication, to delivery at the assembly plant (Information collected includes manufacturing processes, material and information flows, and facility layouts)
2. Collect data on the performance of this manufacturing process: flow time and inventory levels

3. Develop a new shop management process based on TPS
4. Determine how the manufacturing process would change, under the new TPS-based management process
5. Quantify differences between the two systems in terms of flow time and inventory levels (This analysis is presented Chapter 4)
6. Develop an implementation plan for the new process
7. Discuss the design of a new wing skin manufacturing facility

The Product: Wing Skin Panels

Before describing the process by which wing skin panels are manufactured, a physical description of the panels themselves is in order. An aluminum plate is processed into a finished panel which ranges from twenty to one-hundred feet long, varying in thickness from 0.25 to 1.5 inches, and weighing 1000 to 8000 pounds. At the assembly plant, these panels are joined with other structural members (stringers, spar chords, spar webs, ribs, etc.) to form the wing's superstructure. Then additional parts (leading edge, trailing edge, flaps, ailerons, etc.) are added to form the completed wing. Figure 3.1 illustrates the 767 wing assembly which has two upper skin panels, four lower skin panels, and two spar web panels. Note the lower skin panel with the several holes in it---this "enclosure panel" and the web panels are of particular interest in the analysis, for they require the most manual labor.

CURRENT PROCESS AND TPS OPPORTUNITIES

This section describes the current wing skin manufacturing process and changes advocated by TPS ideology. First a summary of the current process is given, followed by a summary of the proposed TPS system. Then each stage of the manufacturing process is discussed in detail, from raw material to finished panels. Then support issues such as scheduling and maintenance are addressed. Throughout this detailed discussion are the improvements offered by TPS.

Note to Boeing readers: Having been at Boeing only six months, and having studied the Skin and Spar shop for only one month, I do not claim to have a complete understanding of the operation. What I do offer is a fresh look at the plant. If there are slight errors in the process description, please look past these to the new ideas offered.

Overview of Current Manufacturing Process

Figure 3.2 summarizes the processing of a wing skin panel from a raw aluminum plate until it's part of a finished airplane. First, aluminum plates are shipped to the skin and spar shop where they are stored and processed. When processing is complete, they are transported to the warehouse (P6) for storage. P6 pulls the various panels and other wing parts out of the warehouse stores, kits them together in long trucks and sends them to the assembly divisions, where the wings are assembled and joined to the rest of the plane. Figure 3.2 also presents data on the shop's overall production rate. Note that "shipset" refers to a complete set of panels required to build one airplane, including spar webs, and excluding panels manufactured outside of this shop.

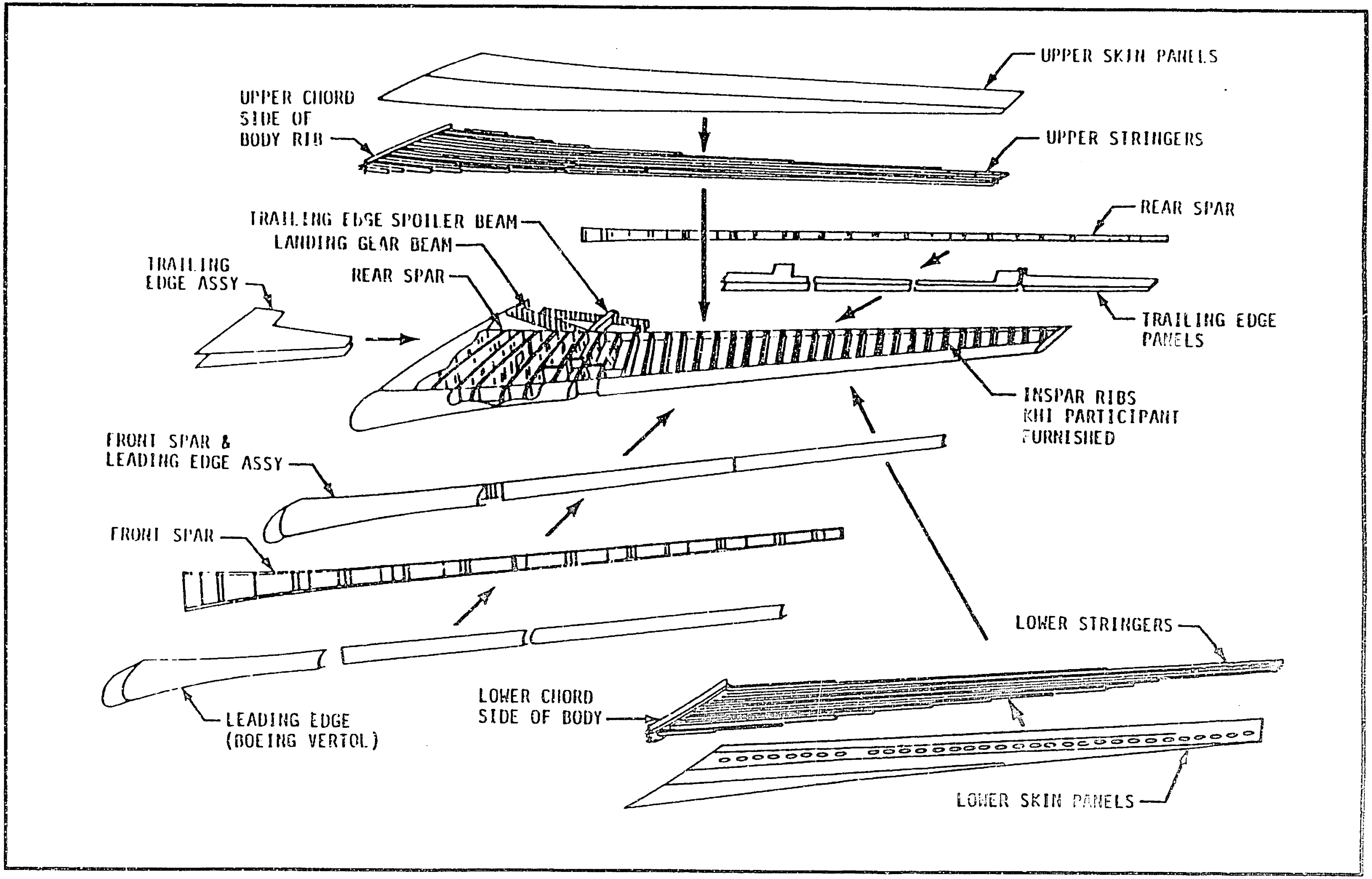
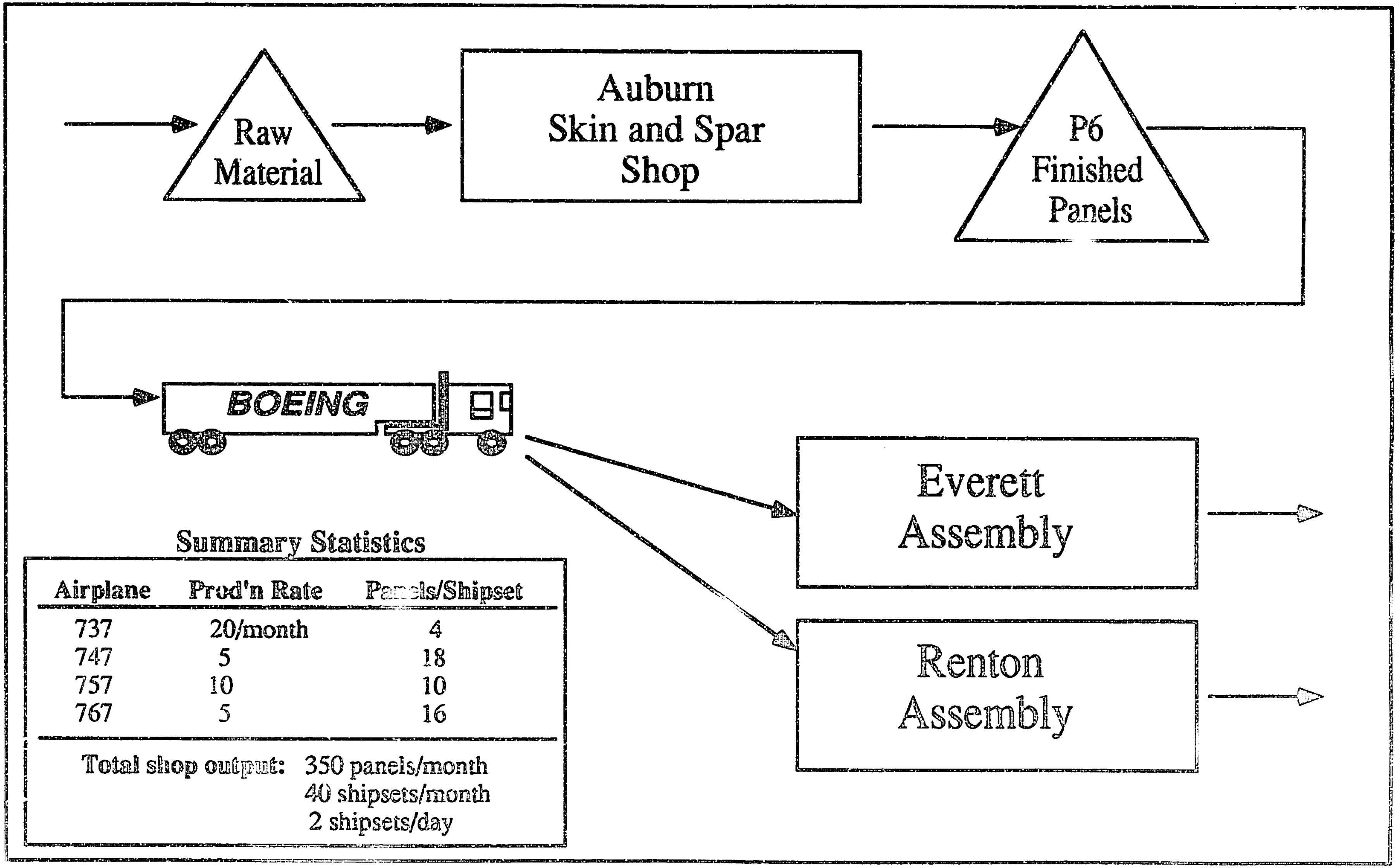


Figure 3.1 767 wing structure



Summary Statistics

Airplane	Prod'n Rate	Panels/Shipset
737	20/month	4
747	5	18
757	10	10
767	5	16

Total shop output: 350 panels/month
40 shipsets/month
2 shipsets/day

Figure 3.2 Overview of wing skin manufacturing process

This investigation focuses on the manufacturing process within the skin and spar shop. Figure 3.3 is a process flow diagram for the shop (Squares represent processes, triangles represent inventory locations, and arrows represent the flow of parts.) It is a fairly linear process with all panels going through nearly identical processing steps. Although there is significant variation in panel size and complexity, there is little variation in the processing method or in the general shape and structure of the finished panels. A simplified description of the manufacturing process follows. More detailed process information is presented later in this chapter.

- **Milling:** Raw material is loaded onto a large, numerically-controlled horizontal mill, held in place by vacuum, and machined to shape. This is done in batches of six to twenty panels.
- **Sanding:** Workers manually sand out marks and burrs left by the mills.
- **Forming:** Deform the root edge of the panel. Then load onto an overhead rail carrier. Carrier moves panel through a series of machines for shot peening, to form curvature and to compression harden the panel's surface. Remove from carrier.
- **Hand work:** While panel lies on sawhorses, workers manually shot peen the edges and cold work holes.
- **Tank line:** Panel is loaded onto a crane and dipped into a series of chemical tanks for corrosion inhibition.
- **Painting**
- **Finishing:** Handling tabs are cut off. Put panel in truck for transport to P6 warehouse.

The upper half of figure 3.4 illustrates the floor layout of the 947,000 ft^2 shop. (The apparently vacant area is used to manufacture chords and stringers, which are processed primarily on separate equipment.) The illustration's lower half shows the flow of a typical panel. Other panels would have similar flows. This diagram shows that though the flow is somewhat convoluted, the process is mainly linear (Fig. 3.3).

Part of the reason for this confused flow comes from the plant's history. Early commercial wing skins (707, 727, 737) were manufactured in Renton, near the assembly plant. When the 747 plant was built in Everett in the late 1960's, the wing component fabrication was centralized in Auburn. Since then the shop has been expanded a few times, to increase capacity and support the newer 757 and 767 airplanes. This gradual expansion contributed to the confused flow.

New TPS-Based Shop Control System

In general, most of the TPS practices are applicable for this shop, as was indicated in the TPS applicability matrix (Fig. 2.3). Because the panels are a standardized product and are produced in uniform volumes, they are excellent candidates for level scheduling, pull, standardized operations, and other TPS practices.

TPS inspires a fundamental shift in thinking for this shop, from a job-shop mindset to a flow-shop mindset. The vision is a level-scheduled, mixed-model processing line, synchronized by pull signals. The plant should think of its process as an assembly line, as part of a larger company-wide synchronized assembly line. This assembly line approach begins with a leveled work schedule, with panels sequenced to reduce the variation on demand for resources. The panels would remain in this same sequence throughout the process. Movement between operations would be based on kanban pull signals to control inventory levels. Work-in-progress would be reduced and pushed upstream to a single stock after the mills.

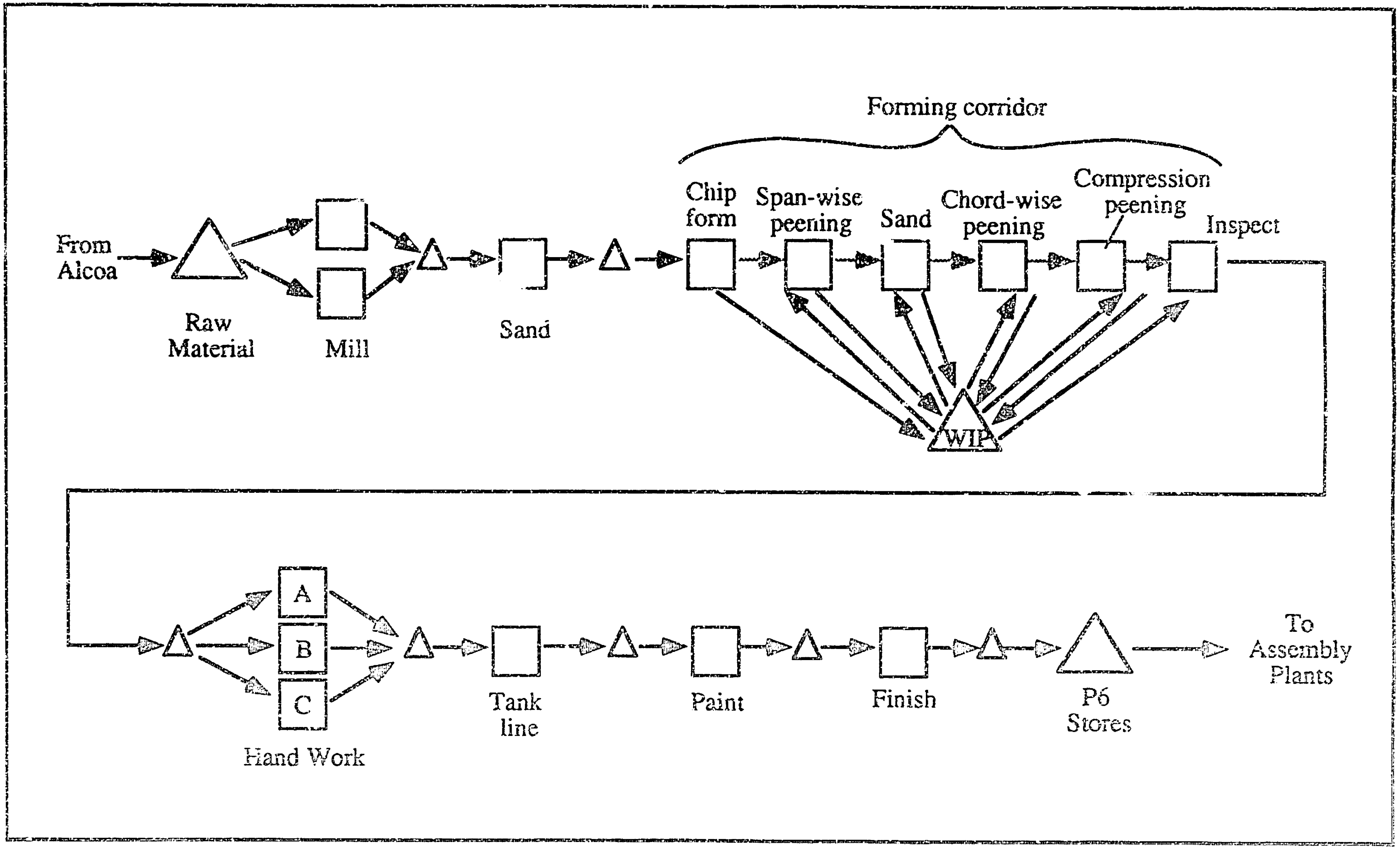


Figure 3.3 Current wing skin panel manufacturing process flow

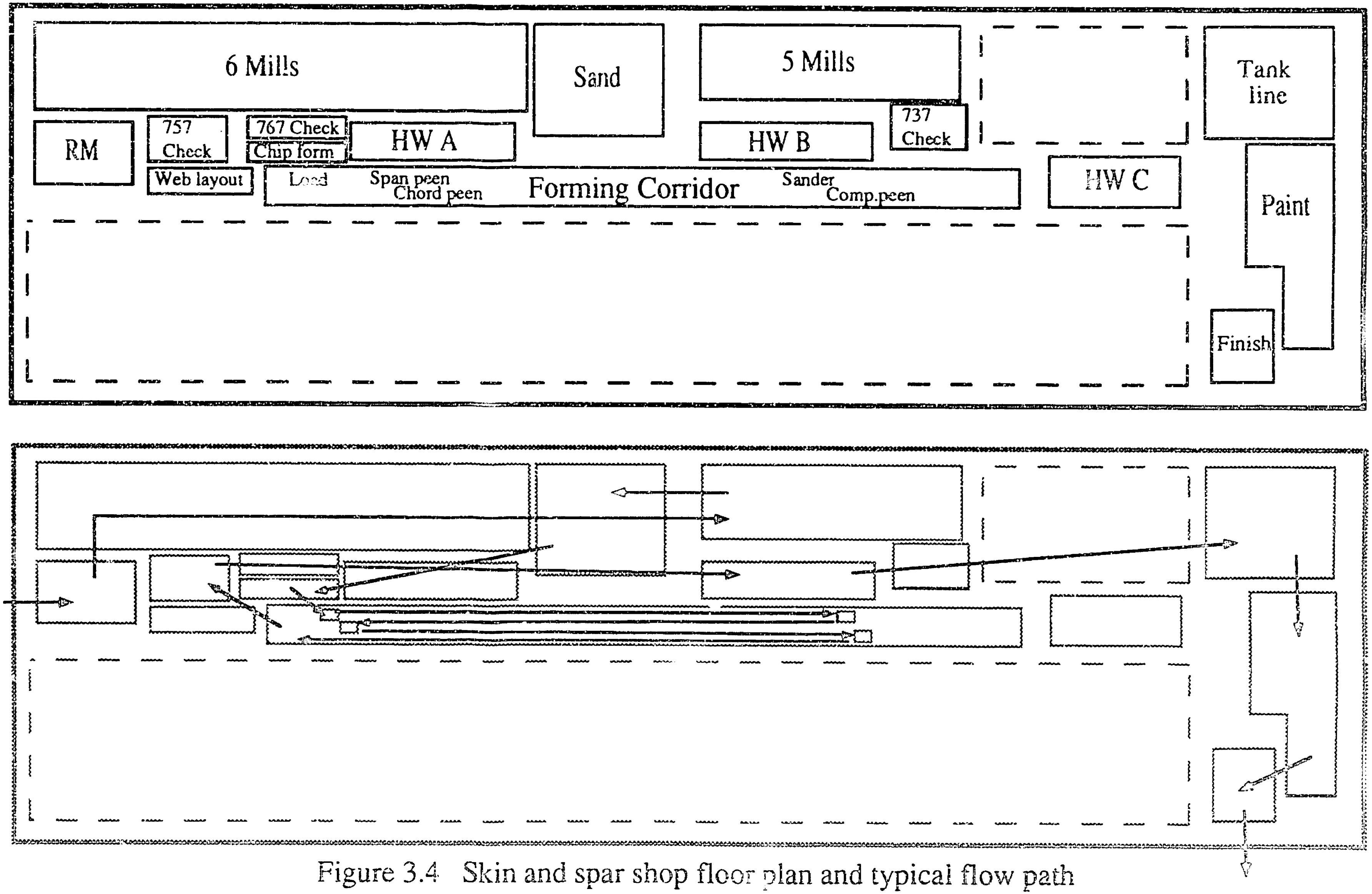


Figure 3.4 Skin and spar shop floor plan and typical flow path

Further development has the plant sequencing the panels so that all the panels comprising a matched shipset are completed on the same day. The logic behind this is as follows: the assembly plants require complete shipsets to build a plane, so P6 should send complete shipsets to the assembly plants, therefore the panels should be manufactured in matching shipsets.

Achieving this level of performance will require management commitment, a few years of hard work, and changes in the plant's culture and plant. Support staffs must assume new roles. Machine maintenance must be improved. The mills must reduce their lot sizes, requiring quicker setup. Internal transportation must be improved to provide smooth, short, quick flow. Processes need to be standardized to reduce variation.

Raw Material

A wing skin panel begins as a slab of aluminum alloy rolled and milled to shape at an Alcoa plant in the Midwestern US. The resulting plates vary from 51" x 184" to 90" x 1248" in size, from 0.25 to 1.5 inches in thickness, and are usually tapered. Weight varies from 1,000 to 8,000 pounds.

These raw material (RM) plates are shipped by train in lots of from five to forty panels, with an average lot size of thirty. When they reach Boeing's skin and spar plant near Seattle, they are inspected, then unloaded using a crane with large suction cups, and stacked on the floor. When the mills need material, raw plates are moved by crane and set on the floor next to the mill.

The plant currently keeps about three to four months' worth of raw material (RM) on hand. About two years ago the plant installed a computer system to keep better track of the RM. Improved tracking accuracy allowed the RM inventory level to be cut in half.

Recommended TPS changes

The computerized inventory tracking system seems to have helped the plant track its RM, but considering the large size and relatively small number of raw plates in the inventory, I would guess the improvement was more due to improved discipline and an understanding of the importance of accuracy, rather than the computer's capabilities. These raw plates are huge and are stored in a highly visible area, making it difficult to lose one.

TPS ideas of visual control and standardized operations can be applied here. The RM is neatly stacked on the floor, with each type of plate having it's own space. If each space were dedicated to a single part number and marked (outline painted on the floor), one could see in a glance how many raw plates are in the shop. As a result, the inventory tracking system could be manually maintained, visually controlled, and still accurate. Simple control obviates the need for computer tracking. Another visual control is to post signs by each stack, to show RM number, current RM quantity, supplier, finished panel part numbers, etc.

If (as described later) the mills reduce their lot size, then the RM inventory can be reduced, with more frequent deliveries of smaller lots. Unfortunately, due to long-term contracts with Alcoa, it may be difficult to change shipment sizes and schedules. Therefore, future contracts should include flexibility of delivery so that Alcoa can modify shipments as the plant reduces its need for RM inventory. In any case, RM reduction should not be an early focus for improvement efforts. First the shop should improve its internal operations.

Milling

The first value-added step in the manufacturing process is machining the RM to give the panel its peripheral shape and sculpted contour.

Machines

There are eleven numerically controlled skin mills in the plant. Five of the machines have beds 12 feet wide and 130 feet long, plus additional length used for parking the gantry which moves along the bed carrying the cutters (Fig 3.5). The other machines have beds 13.5 feet wide and 160 feet long, plus 20 feet at the end for parking the gantry. Each machine gantry has two spindles, meaning it can cut on two panels at the same time, either two identical panels, or mirror images.

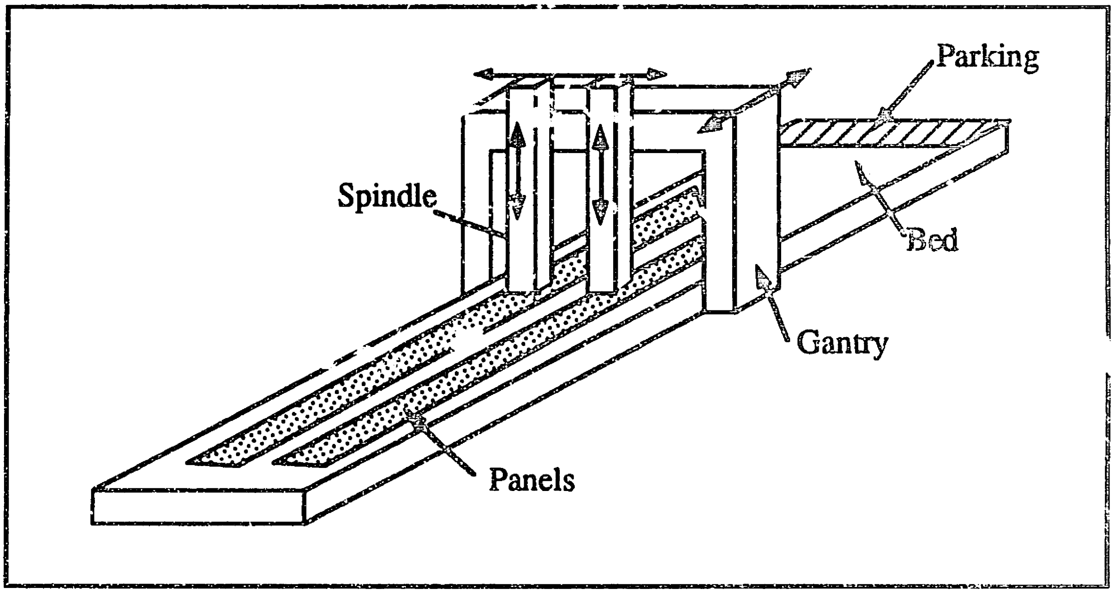


Figure 3.5 Skin mill

Because the panel is thin and flexible, mechanical hold downs such as clamps or bolts would allow the panel to flex and be pulled up by the cutter. Therefore, uniform hold down is needed, so a vacuum system is built into the machine bed. To create an air-tight seal, grooves are cut into the bed in a shape that corresponds to the outline of the panel being milled (Fig. 3.6). Rubber gasket are laid in these grooves and the panel is then placed on the bed. When the vacuum is turned on, the panel is held firmly in place.

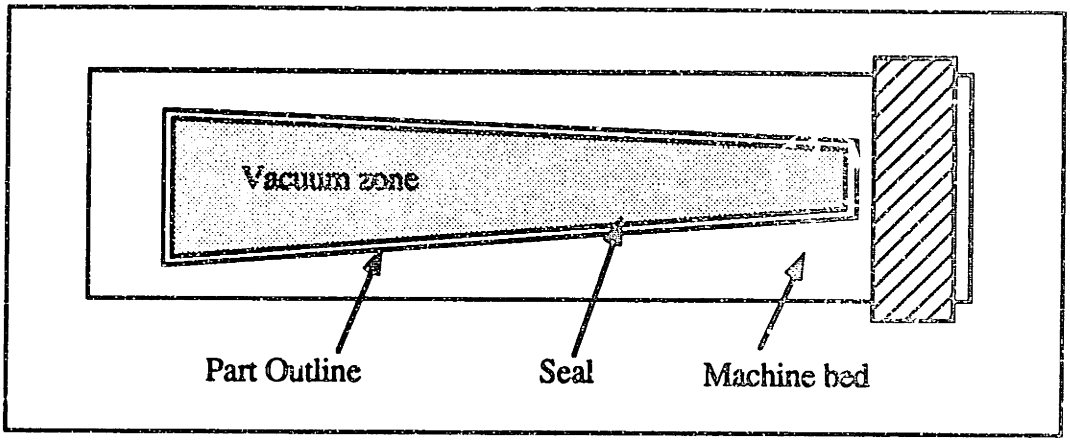


Figure 3.6 Vacuum hold-down system

Since each panel has a different peripheral shape, each requires a different set of seal grooves. There are too many different panels for each bed to have all possible sets of grooves, so each mill has grooves for about five different panels, so machines are restricted to these few specific panels. Each panel has a primary machine, and about half of the panels have a backup machine. Backup machines run the panel only when the primary machine is unavailable.

Machine setup includes several activities. Usually a small portion of the bed must be replaced with one corresponding to curvature of the panel. The bed must be cleaned and deburred, the vacuum gaskets inserted and other activities performed. The entire setup process takes four to eight hours for a simple panel, and up to twelve hours for a large, complex one. While the machine operator has primary responsibility for setups, there are usually a couple extra workers available to help with setups.

The machines range in age from 10 to 20 years, and over the years have become less reliable, caused by maintenance skill dilution as well as machine aging. As a result, downtime is a pernicious problem, currently running around 15%. When other nonproductive time such as setup or maintenance are added, actual cutting time averages about 40% of the available time.

Lot Size

Because of their excessive setup time, the mills run lots. Several years ago, lot sizes were about three months' worth of production. This was cut to two months and finally to one month in mid-1990 with no ill effects. Current monthly production rates and lot sizes are as follows:

Airplane	737	747	757	767
Production rate (airplanes/month)	20	5	10	5
Mill lot size (panels)	20	6	8	6

Figure 3.7 Mill lot sizes

Production Process

Both sides of the RM are milled. The first side milled is the smooth outer surface of the skin, the side visible on the completed airplane. It is called 'media-1,' in reference to the first NC[31] program. When the first side of the first panel is completed, it is stored in a rack, and the next raw panel is loaded onto the machine. This is repeated until media-1 is completed for the whole lot. Then the machine setup is changed to mill the other side of the skin, the sculpted inner surface (called media-2). Because this inner surface is quite complex, with significant amounts of metal being removed, media-2 takes about twice as long to run as media-1. (For example, the run times for a large 767 skin panel are about five hours for media-1, and about ten hours for media 2.) After its media-2 cut, the panel is finished and is placed in a rack to await the next operation, sanding. The milling process just described is that used on the largest panels, those for which the machine bed can hold only one panel at a time.

The machine bed is long enough and wide enough that usually one or more panels will fit on each end of the bed. In this case, one end of the machine is set up for media-1 and the other end for media-2. The raw panels first get the media-1 cut, spend some time in inventory, then are moved to the other end of the machine for the media-2 cut without an intermediate setup. While the gantry is cutting at one end of the machine, the panel is being swapped at the other end of the machine. Note that this multi-panel setup has less idle WIP between media-1 and media-2, as compared to the one-panel configuration described above. Figure 3.8 illustrates three different setup configurations: (1) a single large skin, (2) a pair of smaller identical skins, and (3) a family of upper skin panels for 737. The 737 panels are so small that eight panels (two shipsets) fit on one machine bed.

Proposed TPS Changes

The TPS concepts most applicable to the milling operation are quick setup and small lots. Reducing the lot size reduces work-in-process, but it requires reduced setup times as

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[31] Numerical Control: The mill is called NC because it is controlled by a computer. Each different panel has two NC programs, one for each surface.

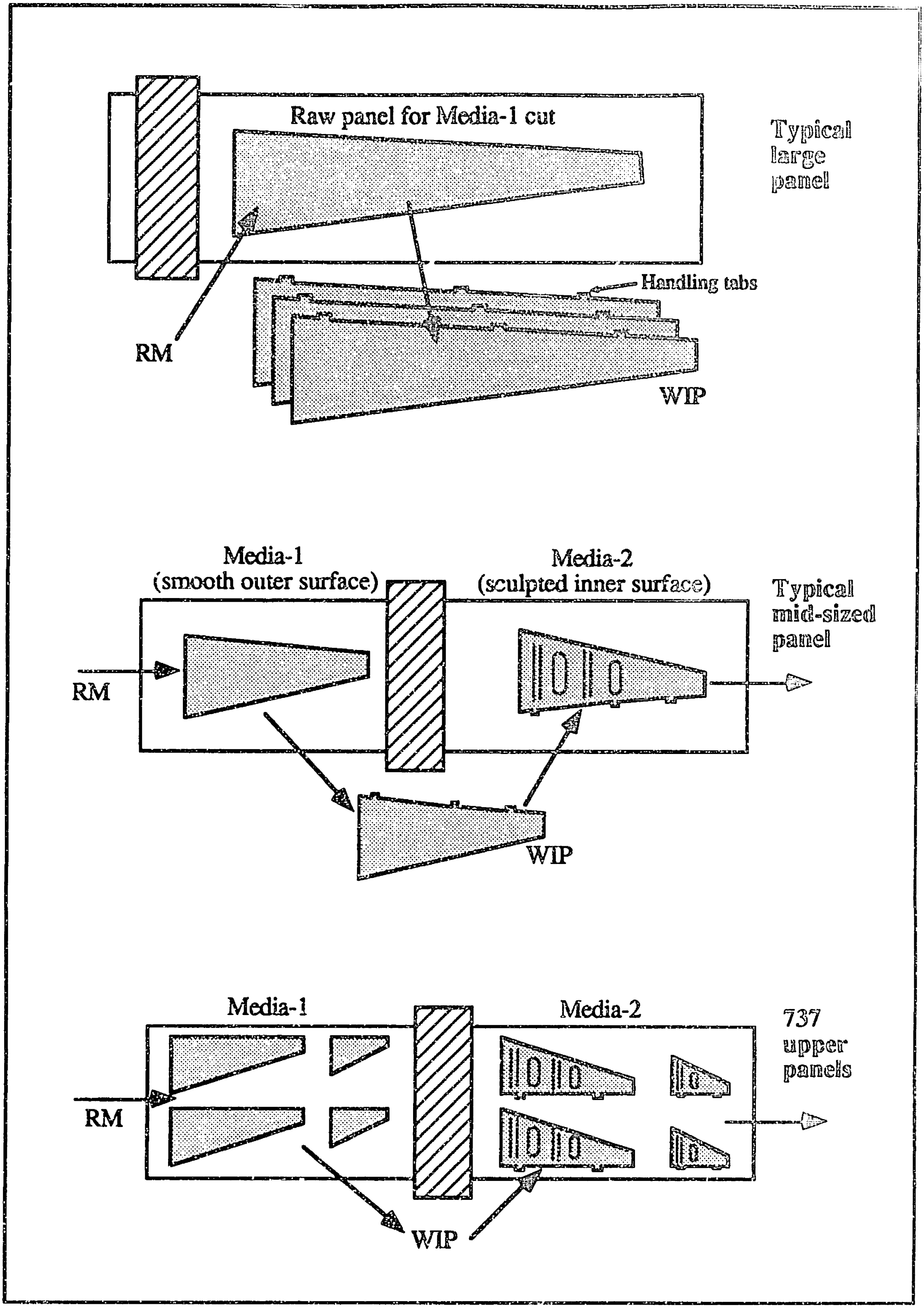

Figure 3.8 Mill bed setup configurations

well. The plant already understands that smaller lots lead to reduced inventory, but quick setup has not been aggressively pursued as the source of lot size reduction.

The motivation for reduced lot sizes is increased responsiveness and reduced inventories. If there is slack time in the milling operation, then lot size can be reduced until the slack time is consumed by the additional setups. This would reduce inventory, but with little gain in responsiveness. If there is no slack time, then setup time must be reduced first, which improves responsiveness and creates some slack time. This slack time could then be used for additional setups and smaller lots, reducing WIP.

The latter "no-slack" approach is probably more fruitful for an organization that sees itself as having no excess resources, as barely keeping up with the schedule (whether in actuality or merely in perception). Therefore, the plant should select a simple but challenging goal for setup time reduction, for example, one-hour setup time. Then reduce lot size, reduce setup, reduce lot size, etc. until lots are one bed full, whether that be one or eight panels. Finally, modify the milling procedures to achieve one-piece flow with all lots sizes of one. More setup ideas follow.

Reducing setup time

A setup reduction project would have to address both technical and management issues. The management issues include reducing worker resistance to analytical improvement methods and time studies, as well as changing perceptions that setup time reduction threatens job security or requires machinists to work harder. Another challenge would be changing work rules, such as having workers help with setups when they're not busy on other jobs, such as crane operators or dispatchers.

Overcoming technical issues would likely require some engineering resources. Here are a few technical ideas. The small part of the machine bed that is changed to accommodate some skins is called the "tooling plate." Currently, these four-foot-square plates are changed using the overhead crane. If the plates are stored right next to the mill on which they're used, they can be swapped with a small, dedicated crane mounted to the mill or a small wheeled crane shared by a couple machines. Another option is to use an air cushion to quickly float the plate between the machine bed and a quick-change cart.

This plant had a true success story in 1990 when setup time for the spar chord mills was reduced from a range of 17 to 35 hours down to just 8 hours. The improvement came primarily from improved organization of the setup teams. It was done with the same hardware, same people, no changes in work rule or job classifications---just better organization and procedures.

Reducing lot size

While setup time is being reduced, lot size should be reduced as well. But in what fashion should lots be reduced? Initially, the reductions should be one bed full at a time, until the lots are just one bed full. Can the lot size be pushed below this one bed full limit? The ideal realization of JIT is one-piece flow, but how can the shop efficiently mill one panel at a time? This problem can be divided into three simplified cases (Fig. 3.9): (1) only one panel fits on the mill bed, (2) two panels fit on the bed end-to-end, (3) two panels fit on the bed side-by-side. In all three cases, the objective is lots in which no two pieces are identical -1-piece flow.

One panel In the case where only one panel fits on the bed, the lot can simply be reduced by one panel at a time until a lot size of one is reached. Doing so will require significantly reduced setup time, since each 1-panel lot would require two setups and the machine must be idle during the entirety of both setups.

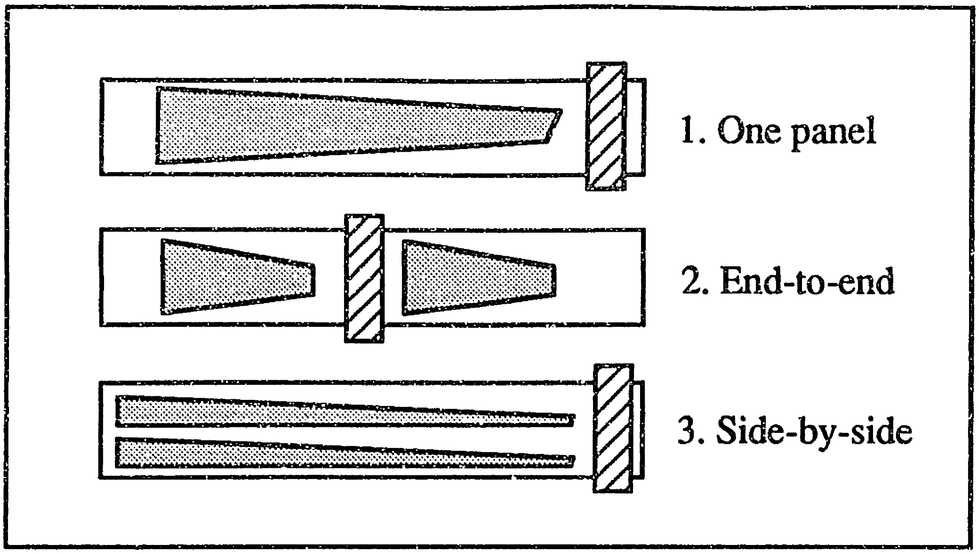

Figure 3.9 Three cases for lot size reduction

End-to-end In this situation there are several approaches to improvement. Recall that media-1 is cut on one end of the mill, and media-2 on the other, with an intermediate WIP panel. Because of the long setup times, both ends are set up for the same type of panel. Then panels are begun on the media-1 end, pass through the WIP station, and are finished on the media-2 end.

If the typical setup and loading time can be reduced until it is slightly less than the typical run time, then these panels can be run in lots of one right away. While the panel at one end of the machine is being milled, the other end of the mill can be set up to run the intermediate WIP panel. As long as the machine runs a class of similar panels, it can run lots of one by continually setting up the idle half of the machine.

The next step is to eliminate the intermediate WIP panel, which presents a technical challenge---moving the panel quickly from the media-1 end of the machine to the media-2 end. The intermediate WIP panel allows loading to be done along with the setup, while the gantry is busy machining the other panel. But if the WIP panel is eliminated, then loading and unloading reduce the available machining time, for the machine cannot be running while the panel is being moved.

Side-by-side In the case where two panels fit side by side (webs, for example), the improvement process is more complex. The first step is the same as for panels where only one fits on the bed. That is, reduce setup time and gradually reduce lot size until running just one bed full (2 panels) in a lot.

Further lot size reduction would require running only one panel at a time. But since the mill has two cutters, it would take just as long to run one panel as to run two. Idling one cutter in this way would be acceptable if there were plenty of slack machine time---but there isn't, so running one panel at a time isn't very feasible.

To reduce the lot size to 1-piece flow while still keeping the machine fully utilized is to run mirror images, matching left and right hand panels. The shop has run mirror images in the past, but has not done so for the past several years, apparently because today's airplanes have differences between left and right panels. If the differences between left and right panels are not extreme, they can still be run together: use one NC program to machine the similar areas in mirror mode, then run the unique portions of one panel followed by the unique portions of the other. This would increase the machine's total run time, but if the differences were minor it may be worth increasing the run time to achieve 1-piece flow on these machines. An additional benefit of running this way is that little if any setup change is required when panels are flipped over to machine the other side, because media-1 on the left hand usually uses the same gaskets as media-2 on the right hand, and vice-versa. Therefore the panels could simply be flipped over and swapped left for right. This setup savings may more than offset the increased run time.

Visual control

The intermediate WIP panels mentioned earlier (the ones between media-1 and media-2) are set on the floor, lying on several pieces of large rope. The area is not painted, marked, or guarded in any way, and my guide acknowledged that these parts are occasionally damaged. As long as the end-to-end milling requires this intermediate WIP piece, the WIP storage location should be cordoned off and marked.

Pull system

In implementing a pull system, the mills must interface with RM storage and with sanding. As long as sufficient RM is in stock, pulling from RM is no problem. The crane can bring raw panels to the mills on an hour's notice.

At the sanding interface, however, there will be a significant problem responding to pull signals, because the milling process is and will remain unresponsive owing to the long machining times. Since the mills can't respond quickly to a pull signal from the sanders, there should be a WIP buffer from which sanders pull milled panels according to their schedule. As setup times and lot sizes are significantly reduced, the mills will become more responsive, and the WIP buffer size can be reduced. When the mills are finally capable of one-piece lots, then they can respond to pure pull signals with a buffer of only one of each part number. More about this is presented in Chapter 4.

Sanding

In this process, a crane takes a panel from a WIP rack and lays it across sawhorses. Then workers sand and debur it with power hand tools (disk sanders, belt sanders, etc.).

The panel is then flipped over by a crane to allow sanding the other side. Completed panels are returned to WIP by a crane. Processing time varies from five to twenty hours.

Proposed TPS Changes

The TPS benefits here include leveling, standard work, multi-function workers, and quick setup. The process already has one-piece flow. Leveling is achieved by developing a fixed processing sequence rather than running by priority. Standard work could be used to reduce the variation in processing times. Multi-function workers here and in handwork (the two labor-intensive operations) could allow moving workers back and forth to offset fluctuations in labor demand.

Setup time could be reduced by improving how the crane lifts these panels. Rather than tying ropes onto the handling tabs, use a crane bar with rigid hooks. Positioning of the sawhorses can be sped up by putting them on wheels.

Chip Forming

In this process a crane operator brings a panel and lays it on a large table. Then an operator uses a hydraulic press to bend the panel's root (the end of the panel which attaches to the airplane fuselage), imparting a front-to rear curvature. This is done prior to peening because the peening process is unable to impart sufficient curvature in this thickest section of the panel. Chip forming (also called bump forming in other industries) requires a great deal of skill, and there is a lack of experienced operators. When finished, the panel is moved by crane to a WIP rack near the forming corridor's rail loading area. Note that not all panels receive this treatment.

Forming

This is the most complex area in the plant and is currently the plant's bottleneck operation. It is actually several interrelated processes, linked by a dedicated transportation system. In preview: after chip forming, panels are loaded onto an overhead rail transportation system, shot peened, machine sanded, shot peened again, unloaded, and inspected for contour. Figure 3.10 illustrates the forming process layout, figure 3.4 shows the flow of a typical panel through the forming process.

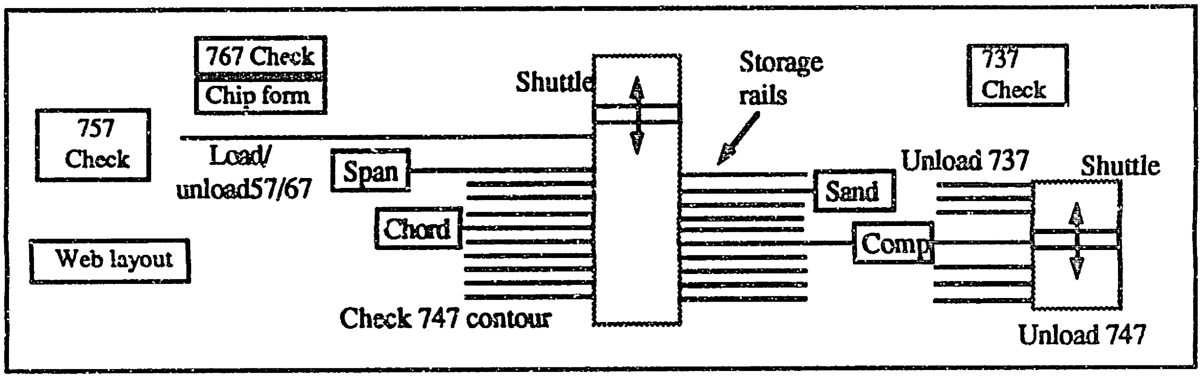

Figure 3.10 Forming process layout

In the shot-peening process, developed internally by Boeing, streams of steel shot impact the panel, imparting a curvature and compression hardening the surface. The entire panel surface is peened, except some small areas which are masked. Webs are compression peened only.

Rail Carrier

After chip forming, panels are bolted to carrier plates from which they hang as they travel along the overhead rail system (Fig. 3.11). These rails store and transport panels between various stages in the forming process. In figure 3.3 (shop process flow diagram) the forming corridor includes a WIP triangle, which represents the rail system; the light arrows indicate that panels can flow directly from one process to the next, while the dark arrows indicate that panels usually are stored between forming processes. In the center of this transportation system is a shuttle for shifting the carriers from one rail to another. When this shuttle breaks down, the whole forming operation is brought to a halt.

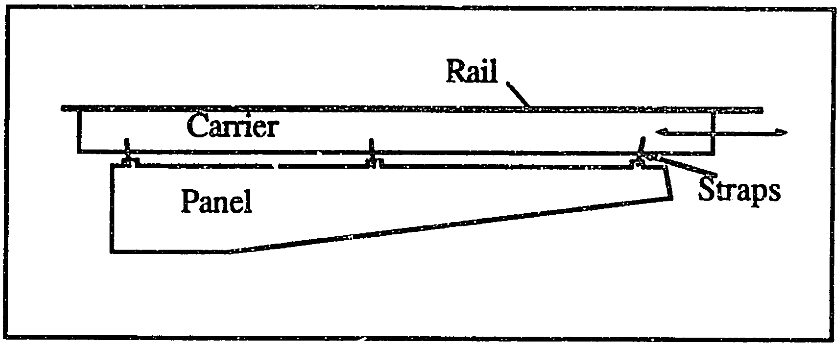

Figure 3.11 Panel loaded onto rail carrier

When a panel is loaded from a WIP rack onto a carrier, it is also washed, and some areas of the panel are masked to protect them from the peening process. Then the carrier and panel are sent to an overhead storage area.

Span-wise peening and sanding

Span-wise peening, used only on the newer airplanes, imparts root-to-tip curvature (Fig. 3.12). After span-wise peening, the panel is stored until it can be moved into the sanding machine. Because span-wise peening leaves the panel's surface rough, it must be sanded, which is done inside an enclosed machine. The operator looks through a window and tele-operates the sanding head. After sanding, the panel is returned to overhead storage.

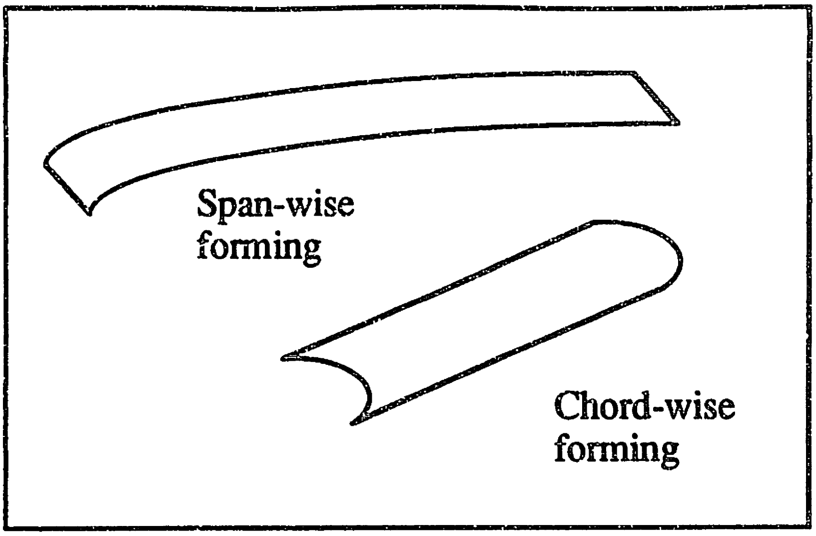

Figure 3.12 The effects of span- and chord-wise peening

Chord-wise peening

Chord-wise is the original peening form process and has been used since the 727. It imparts a front-to-rear curvature in the panel (Fig. 3.12). All skin panels go through this machine, both uppers and lowers (not webs). After this machine, the panel returns to storage. The chord-wise machine can also serve as a backup for the compression machine. Changeover takes about an hour.

Compression peening

Compression peening is done on all panels, including webs, to compression harden the surface for improved fatigue life. After this machine, panels are inspected for surface properties, then unloaded from their carriers and placed in a WIP storage rack

Proposed TPS Changes

The forming machines all process panels in lot size of one, so quick machine setup is already a reality here. A pull linkage back to the sanders should be rather simple to set up. Since sanding is a manual process, there is enough flexibility there to quickly respond to forming's needs. A link forward to handwork would be harder to develop, though, because forming is the bottleneck. Until the forming flow can be smoothed out, a buffer will be needed between forming and handwork.

The quickest route to improving the forming bottleneck seems to be reducing the constant shuttling of panels along the overhead rail system. This is caused mainly by the machine layout, which is designed for maximum flexibility (and maximum shuttling, as well). Moving machines is a severe step, but one that seems appropriate according to TPS principles. Since all span-wise peened panels are sanded, the sanding machine should be directly in line after the span-wise machine. This layout would reduce the current level of flexibility, but if the machines are reliable and the processes under control, then there is no need to design for independent operation. If some unmasking or inspection needs to be done between the machines, set them with a gap for one WIP panel in between.

Other less-severe ways to reduce the shuttle bottleneck are to perform PM on the shuttle system. Also, eliminate unnecessary shuttle moves, such as driving panels from the compression machine all the way back to the load area for unloading. Unload the parts near the last machine if possible.

As mentioned previously, the chord-wise machine can also do compression peening. If the changeover time could be reduced to a few minutes, then the chord-wise machine could be used to compression peen panels immediately after they are chord-wise peened. Even better would be to modify the compression-peening machine so it could perform chord-wise peening as well. Then both machines could be used for both purposes, and panels would require less transportation, easing the rail shuttle bottleneck.

Inspect Contour

Though there is inspection throughout the entire panel manufacturing process, contour inspection is the most significant to process flow. 747 panels are inspected after chord-wise peening---the panel and carrier are lowered to floor level, and large templates are held against the panel to check the contour. After inspection they are returned to overhead storage.

Panels other than 747 are inspected after compression peening. They are moved by crane and laid on large check fixtures. Each fixture simulates the upper or lower half of a wing's superstructure sans skins, so laying a panel on the fixture simulates assembling the wing. Each fixture checks all the panels on either the upper or lower surface of either the left or right wing. Since each wing surface consists of more than one panel, each fixture checks more than one panel, but only one panel at a time is checked due to the handling tabs which would cause adjacent panels to interfere. The contour inspection process consists of laying sandbags on the skin to simulate the pull-down force of rivets used in assembly. If this weight presses the panel down into sufficient contact with the fixture, it passes inspection. If not, localized peening is used to finesse the shape. After this inspection, a crane moves the panel back to a storage rack.

Hand Work

As implied by the name, hand work is a manual process. Cranes brings panels from WIP racks and lay them on sawhorses. The manual work includes shot peening, where a portable machine is used to compression peen parts of the panel that the large peening machine can't access. Small holes are cold worked by pulling a mandrel through them. Processing time varies from 10 to 40 hours for the various panels.

Handwork is performed in three areas of the plant: area A is near the mills and does 757 and 767 panels. Area B is near the peening machines and does 737, 757, and 767 panels. Area C, most organized of the three, is near the tank line and does all of the 747 panels. All the panels used to get hand work done in the area now called C; the other two areas were added in the last few years due to increases in the amount of handwork done on each panel.

After the hand work is done and while the panel is still on the sawhorses, the panel is inspected for hole sizes, peening characteristics, thickness, hardness, etc. A mylar template is also rolled out on the panel to inspect the size and location of pads, holes, etc. The webs receive a similar inspection but it is performed on layout tables at the end of the shop, near where the forming rail carrier is loaded; they are checked for flatness and against a mylar. Finished panels are returned to a WIP rack or taken directly to the tank line loading area.

Proposed TPS Changes

This department already runs lot-size of one. Quicker setup could be achieved through better organization of tools and workers. Since this is a bottleneck operation, a pull linkage would be difficult to achieve, though easier with the tank line than with forming. Hand work was divided into three areas because of a need to spread out when the workload increased significantly, but it introduced obstacles to smooth flow: difficulty in shifting workers throughout the day as workload fluctuates, redundant equipment needs, long crane moves, etc. Recombining the areas and placing them near the check fixtures could reduce some of these problems. But there would likely be little room to do this until the WIP level is reduced to clear out some racks. Standard work would also be helpful to reduce the wide variation in processing times.

Tank Line

The next processing step is the tank line, a series of chemical tanks into which the panels are dipped to improve corrosion resistance. This process, as well as the subsequent ones, is shared with the chords and stringers, wing components manufactured in another part of the plant.

Panels are moved by crane to a special rack. There they are rigidly attached to a rail carrier, in similar fashion to the peening process. Each rail can hold from one large 747 skin to four small 737 skins. The rail is then moved onto a carrier (Each carrier can hold one or two rails.) This carrier is then moved by crane between the various tanks (Fig. 3.13).

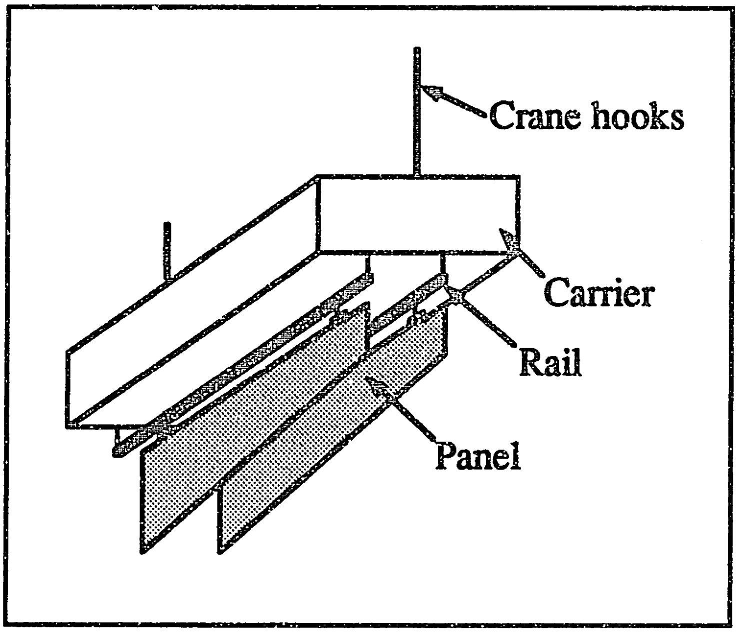

Figure 3.13 Tank line carrier with panels

Various aluminum alloys are used for different panels, requiring different processing times in some tanks. Fortunately, these alloys can be grouped into just two categories, 2XXX and 7XXX. Since the two groups have different processing times, all the panels on a given carrier must be in the same group. To fill a carrier, the loading worker looks at the computer scheduling system to see which WIP panel has the highest priority. He loads that panel and then other panels of the same alloy group to fill the carrier.

The tank line process begins with a few minutes in an etching tank, which removes a thin layer of material. The timing here is critical, so test samples are etched each week to determine the current etching rate and resultant nominal etching times for the two alloy groups. Following the etch are two rinse tanks for a few minutes each. Then the panel spends ten minutes in a tank of deoxidizer to remove etchant residue and iron oxide left by the steel peening media. This is followed by two more rinses. The next tank is for anodizing, to improve corrosion resistance. At forty to sixty minutes, this tank takes the longest. After two more rinses, the final step is 24 minutes in a tank of chromic acid sealer, which hardens the surface to further improve corrosion resistance.

Following this tank line process, the rails are removed from the carrier and put into a storage area to cool down for thirty to forty-five minutes. Then QC checks the panel surface quality. For enclosure panels (the ones with fuel compartment access door openings) the openings must be specially treated before they can be painted.

Proposed TPS Changes

This line was the plant's bottleneck until 1990. Though it is no longer the bottleneck, overtime is still high. Since the process is straightforward, moving carriers from one tank to the next, the problems must be in controlling the process. Therefore, to smooth the flow requires process control. Only when machine availability and reliability are improved can the tank respond to pull signals from the next operation, paint. A prime challenge with this process is keeping the chemical solutions in balance. Daily chemical checks (preventive maintenance) can aid in keeping this balance.

One way to improve throughput is to deliver panels to the rail load area in groups of the same alloy, so that full rails can be run without delay.

Visual control has several applications here, such as clearer postings of alloy groupings, processing times, etc. Also, a large digital count-down timer could be installed at each tank so that when an operator puts in a carrier of parts, he can hit a button corresponding to group 2XXX or 7XXX to start the countdown, and can then easily keep track of where each tank is in it's cycle. For time-sensitive operations such as etching, add colored beacon lights or alarms to warn when the timer is near completion.

Paint

As is the tank line, paint is shared with the stringers and chords. The process begins when rails from the tank line are moved from the storage area into the paint booth. There the panels (or chords or stingers) are electrostatically painted with a primer. Then the rails move into another queuing area for a while before going into an oven for a one-hour bake at 180°F. After cooling off from the oven, the panels are unloaded from the rails into special racks for the finishing operations.

Proposed TPS Changes

The paint operation is already very smooth, with one-piece flow and no setup time restrictions. This area is the last one the plant should worry about. It could. however, benefit from a pull linkage with the finishing operation as well as some simple TPS methods such as a timer for the oven, to signal when the one-hour bake is done.

Finishing

The finishing process provides final preparation of the panels before transport to the P6 warehouse. It basically involves sawing off the handling tabs which were machined into the panel to facilitate transportation (shown in Fig. 3.8) The metal exposed by this sawing is then shot peened, chemically treated, and painted. The panels are then loaded into special trailers, which, when full, transport them to the P6 warehouse.

Proposed TPS Changes

Like the paint process, there are few obstacles here, though TPS methods such as standardized work do offer some improvement. There is a possible benefit to a process change, though: since the panels are handled several times after they leave the shop, why not leave the tabs on until the panels arrive at the assembly plant, to facilitate easier handling? Once the tabs are removed, the panels are lifted by a simple pinch clamp that is held shut by the panel's weight, but which can damage the panel if used incorrectly. This minor process change could prevent damage and reduce waste, although the benefits would have to be weighed against the impact of having the assembly plants remove the tabs.

P6 Stores

All finished skin and spar parts are sent to and stored in P6, a separate building on the Auburn site, where parts are stored in racks, kitted, loaded into special trailers, and trucked to the assembly plants. A kit is a matched set of parts needed at the same time by a particular assembly plant operation, such as all the skin panels and stringers for the upper half of a set [illegible]7 wings. The kit includes components supplied by the skin and spar shop, other Boeing shops, and outside vendors. The delivery trailers are 120 feet long, with a driver steering in back. Due to their size, their travel hours are legally restricted. They are also unstable in strong winds, so bad weather can delay shipments. Kit size varies: two complete 737 kits fit in a single trailer, while it takes seven truckloads for a single 747 kit.

The current inventory level in P6 is about three or four weeks for skin and spar components. Kits are delivered to the assembly plant approximately one week before they're scheduled to be loaded into the assembly fixtures.

Proposed TPS Changes

The first stage of TPS application is to see how TPS could help P6 run more smoothly; the second stage is to change P6's role. Since the assembly plant schedule is set months in advance and the customer demand is known years in advance, there is little benefit to a pull system between P6 and the assembly plant. The current computer scheduling system is a sensible way to schedule kit deliveries to the assembly plants. However, the computer link between P6 and the skin and spar shop could be replaced by a simple pull linkage. When the skin and spar shop has its process under control, it could resupply P6 on a pull basis. When this becomes possible, it is time to eliminate P6, or at least to redefine its role.

What is P6's role? In Toyota's way of thinking, P6 is 100% waste, since it is filled with idle capital goods of immense cost. But for Boeing it is currently a necessity; since the plants cannot produce components in complete kits, parts must be accumulated somewhere. Also, since output from the shops is unpredictable because of breakdowns and other interruptions, the inventory represents an insurance policy to keep the assembly plants supplied. (This is the same reason U.S. automobile plants used to keep weeks' worth of inventory on hand.) As the skin and spar shop becomes more predictable and reliable, the P6 inventory level can be reduced. Whatever safety stock P6 decides to keep on hand, it should be in integral shipsets---a partial set is useless.

The next question whether the reasons for P6's existence can be changed, or can P6 be eliminated altogether? If the skin and spar shop gets its process under control to where there is an internal pull system, quality is under control with tight feedback loops, and WIP and flow time are reduced, then there is a way to eliminate the skin panels from P6: develop a new scheduling system for the skin and spar shop that schedules panels to be completed in shipsets. That is, if a 757 kit is needed on Tuesday, schedule the shop so all ten panels in that kit are completed on Monday. This proposal is expanded upon throughout this chapter and the next.

If the shop could process panels in matched shipsets, then redundant handling by P6 could be eliminated. The shop could load finished panels into the trailer as usual, then send it to P6. But instead of P6 unloading the trailer to store the panels, it would just add the stringers, chords, and vendor parts to the kit and then send it off to the assembly plant.[32] P6's role then becomes one of managing vendor parts and providing a small safety stock. It may appear contrary to TPS ideals to condone safety stock, but stockless production is many years away for this shop. The eventual goal may be a balance between pragmatism (safety stock) and idealism (no buffers of any kind), maybe one or a few of each panel to cover for scrap, or a temporary machine breakdown. Trailers leaving the skin and spar shop with a short shipset could stop at P6 to pick up a replacement panel for the

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[32] Notice that the stringers and chords were mentioned as still being stored in P6. It would be desirable for these to be built in shipsets as well, but the current manufacturing process makes 1-piece flow processing even more difficult for these components than it is for the panels. This thesis does not include them in the analysis.

one that was scrapped or delayed in the plant. This new approach allows for a much smaller P6 facility.

Shop Flow Management

So far, this chapter has discussed how TPS applies to each separate manufacturing operation. This next section addresses the internal linkages, how all the processes tie together. "Shop flow management" refers to the policies and methods of where material is stored, when it is processed, how much inventory is maintained, etc.

The shop flow is currently managed basically as a one-piece-flow push system. Milling is done in lots of six to twenty panels, but the rest of the shop runs with lot size of one. The post-mill processes run panels based on their priority. An ADP (Automated Dispatch Panel) computer screen shows the priority of each panel so that the highest priority panels can be run first, but operators can override the system's recommendation. Priorities are recalculated daily and are based on the number of physical moves each part made in the previous day. Because the sequence is based on priority rather than availability of the next process, it results in a "push" manufacturing system, where each process "pushes" panels to the next process as fast as it can.

The method currently used to set priorities destabilizes the shop's flow in a few ways. First, it allows low-priority panels to be neglected so that WIP builds up. When these panels have sat long enough for their priority to go up, then they are processed several steps through the shop, which causes their priority to drop, so the panels can once again sit around until their priority goes up again. This lurching effect destabilizes flow through the plant. The second effect is variation in flow time. Since each panel is prioritized individually, they are constantly leapfrogging one another, causing the actual flow times to vary widely. For example, an average panel is completed in 40 days, but 737 panels go through the shop in only 13 days. Since 737 panels are high volume and simpler than others, the shop runs them through quickly to keep WIP counts down.

Proposed TPS Changes

Because this shop has a consistent process plan, complete ownership of the part from raw material to P6, and little product or schedule variation, it is a perfect candidate for a pull system. This cannot be said for all Boeing plants, but for this one it is clear. Many of the required changes have already been alluded to in previous portions of this chapter. In general, the post-mill operations that are already able to do one-piece flow should refine their scheduling to reduce their WIP and so they can run panels in a fixed sequence, which means keeping the panels in the same sequence through the whole process---no more leapfrogging. The prerequisites for this, such as improved machine reliability and quality control feedback, are addressed later.

To reduce WIP, begin by controlling which WIP racks are used by each process in the plant. Also, specify a standard number of panels to be in each process. As process variation is reduced and reliability improved, gradually restrict the amount of WIP between processes. Instill an understanding that if the WIP rack is full, stop processing until the next operation catches up. Each WIP storage area should have minimum, nominal, and maximum WIP level specifications so workers know when processes are getting out of balance.

In addition to general WIP reduction, some remaining WIP should be shifted upstream to a stock after the mills. This provides a buffer so that the mills which produce in lots can provide sequenced panels to the shop.

Material Handling

Handling of panels is primarily by radio-operated overhead cranes. Raw panels are moved by a special crane with large suction cups. WIP panels are suspended by straps tied to the handling tabs milled into the panels. Finished panels are lifted with pinch clamps. The cranes are sometimes a bottleneck, due in part to frequent break-downs.

Proposed TPS Changes

The material handling system must support the desired shop flow management methods; they must be mutually supportive. The proposed pull system raises the pressure for rapid and timely crane moves, though it actually reduces the total number of moves required. Raw material would be moved to the mills more frequently, since it would be milled in smaller lots, which might also require more frequent sling changes. But the total number of RM crane moves would be unchanged or reduced. WIP handling would become increasingly urgent due to reduced WIP idle time, but the handling would also become less frequent, since with less WIP there is less shuffling around of panels. When a pull system is in place with WIP levels down, cranes can take panels straight from one process to another, without intermediate WIP storage. Providing this higher level of responsiveness may require more cranes and crane operators. An effective solution is to have some or all of the machinists qualified to operate the crane, rather than having dedicated crane operators.

Improved plant layout can smooth the flow of materials and reduce handling. For example, many of the crane moves carry panels across large portions of the plant's length, repeatedly going back and forth. Better locations of manual work areas (sanding, checking fixtures, handwork and finishing) could reduce the interference caused by cranes traveling the plant's full length.

Better crane maintenance will improve reliability. And visual control has some uses. For example, the next panel to be picked up from any process could be marked with a flag.

Scheduling: Planning and Tracking

Shop scheduling is currently a two-phase process. First, orders from the assembly divisions for individual panels are grouped into lots and scheduled to be run on the mills (planning). Second, after milling, individual panels are scheduled through the rest of the shop based on priority (shop floor tracking).

Planning

Currently the corporate computer scheduling system plans for panels to be released to the mills 80 days (four months) before they're due in P6, which in turn is 15 days (three weeks) before P6 is scheduled to kit the parts and send them to the assembly plant. All panels are given the same scheduled flow time, regardless of their complexity, but the actual flow times vary. The shop has set its target flow time at 51 days, more aggressive than the corporate plan of 80 days. Currently, actual performance is even better, about 40 days from mill to completion.

Shop Floor Tracking

Once a panel is begun on the mills, it is tracked through the shop by a computerized system. The tracking system monitors the progress of each panel through the shop, recording the time each worker spends working on each panel. Labor hours are recorded and tracked very closely, but the system doesn't differentiate how much of the time is spent on specific activities. Because the tracking system does not break the work time down into its elements, there is no information on machine run times, for instance, although labor hour data is abundant.

As the assembly plant's production schedule changes (for example, if a customer cancels an airplane) the priorities of panels in the shop can change. Sometimes the schedule is disrupted by emergency parts such as AOG[33]. Priorities are also shuffled due to bottlenecks or breakdowns in the shop. Other schedule disruptions are caused by tool, tape, and part tryouts for new airplane designs.

Proposed TPS Changes

TPS advocates care in planning and simplicity in tracking. Actually, TPS eliminates much of the need for tracking, for with low inventories and processes linked by pull signals, detailed tracking is not needed. The recommended scheduling system supports the previously-described pull system and has the following characteristics:

1. Since Boeing doesn't build fractional airplanes, but only whole ones, scheduling should be based on whole shipsets rather than individual panels
2. Schedule the shipsets so they are produced in the same order as needed by the assembly plants
3. Within a given shipset, sequence the panels to level demand on resources

Simple systems and visual control can be used for planning production and for tracking inventory through the shop. At first, use a manual system, or a simple computer model. Once the level sequence scheduling is understood and running smoothly, then automate it. The current shop floor computer tracking system should be used to track and measure run times and to record process data for improvement efforts. The scheduling

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[33] Airplane-On-Ground, which means a customer's airplane has been damaged in service and needs a new skin, which is not normally stocked in spare parts warehouses.

computer is de-emphasized because until the pull system is developed, proper software can't be designed. If the computer system is designed too soon, it might result in a system which doesn't meet the shop's needs, which could drive the plant to sub-optimize its process, matching its scheduling practices to the computer's needs rather than vice-versa.

To visually assist in tracking WIP, post a board on each WIP rack to show what panel is in each of the rack's slots and when each arrived. For the panels currently in process (i.e. being sanded, etc.), have a board showing where each WIP panel is in the process.

This is the only Auburn fabrication shop that develops its own schedules---other shops are scheduled by a corporate system. This freedom gives the shop flexibility to experiment with its schedule. Chapter 4 presents a model of a level-scheduled, mixed-model processing line, synchronized by pull signals. This assembly line approach uses the current aggregate planning for raw material and pull signals for production control.

Measurements/Incentives

Fabrication division performance measurements currently focus on manpower: labor efficiency (labor usage compared to standards), head count, and overtime. The focus on labor utilization creates pressure for workers to always be busy (which leads to higher post-process WIP levels) and to slow down when pre-process WIP begins running low. It also can encourage a department to ignore the computer system's priority assignments in selecting which panel to work on. Supervisors could select panels which are known to have favorable labor variances, leaving the unfavorable panels for the next shift to process.

The various skin and spar shop processes are measured and compared on the number of panels completed each day. This creates an incentive to push panels on to the next operation, regardless of whether the next process is ready for them. Each department may also try to process the easy panels first to get its counts up. The result of this incentive is that 737 panels go through the shop in just 13 days, compared to the shop average of 40 days. The success of one shift in completing a large number of simple panels leaves the next shift to process the large, difficult panels, making their counts look bad. Though there is some evidence of the measurement system being manipulated, it is not clear how large a problem this has become.

Labor efficiency measurements are based on the ratio of standard labor time allowed to actual labor time used. A problem with this system is that the standards are based on I.E. studies performed in the 1950's for generic machines and processes (ex., drilling, deburring, etc.) used at that time. It is questionable how relevant the standards are for today's panel designs and processes.

Proposed TPS Changes

Performance measurements of labor efficiency and part counts originated in labor-intensive "push" manufacturing systems. They are not conducive to a JIT system, because they encourage overproduction. And they can, ironically, discourage process improvement.

Before the plant can begin to pursue a leveled pull system as recommended, appropriate performance measurements must be adopted. Shop management must agree to reduce emphasis on traditional monitoring-oriented metrics and focus more on improvement-oriented metrics. Metrics that support JIT include quality, process variation, setup time, total cost, lead time, flow time, touch time, inventory levels, conformance to schedule, etc. "Conformance to schedule" refers not to the number of panels through each process, but conformance to the fixed sequence, which should remove the incentive to push easy parts through the system for counts.

Such a new performance measurement system would create a new role for the shop's I.E. (Industrial Engineering) group. Currently, their work is mostly related to tracking labor hours. They don't time study their processes or measure actual machine setup and run times. This group is the logical one to organize and begin process improvement efforts which begin with quantifying the current process.

Maintenance

Machine maintenance is a major problem in this plant, and machine breakdowns are the biggest bottleneck to flow, according to the I.E. department. The causes seem to be the nature of preventive maintenance (PM), the experience level of the maintenance personnel, and the plant's organizational structure.

Major PM is scheduled on each mill at six-month intervals, but the machines rarely run that long without breaking down. Because the major PM takes so long (a week or more), some production managers and machine operators are reluctant to shut down a running machine. This is caused by schedule pressures and lack of trust. The problem is exacerbated by the fact that maintenance workers don't have the authority to shut down machines at their discretion. There is a shortage of trained maintenance workers, and the current skill base is being diluted by the transfer of some maintenance personnel to the new skin and spar shop. It takes over a year to train a new maintenance person.

The plant does have a great example of one TPS technique, visual control. Large annunciator boards are mounted high on some of the columns are used to call tradesmen. The board tells which trade is needed and where.

Proposed TPS Changes

The first priority in maintenance should be to overcome the current lack of trust between maintenance and production personnel. This should begin with agreement on the benefits and nature of PM. All parties seem to think breakdowns are inevitable and acceptable as long as kept under control. This perception must be changed, and machine reliability must be pursued. Toyota demonstrates repeatedly that 99% machine uptime is sustainable, even on old equipment.

High levels of reliability require proper maintenance. Toyota has machine operators perform PM on their own machines, activities such as daily machine inspections and lubrication. If this shop is unable to arrange for machine operators to perform PM, then one maintenance person could be assigned to check all the machines on a daily basis: oil, filters, air hoses, etc. This could be done by a relatively new person, as he wouldn't need to know how to fix the machine himself. This person can be thought of as a General Practitioner, while the more experienced maintenance people are more akin to surgeons, and are called in by the G.P. when major work is needed. Though only mills are discussed here, the maintenance problems and TPS solutions also characterize the peening machines and material handling systems.

SUMMARY OF TPS PROCESS

This summary is a recap of the conclusions and recommendations presented in the detailed discussion above.

- Mills: pursue quick setup to allow small lot production; PM

- Sanding: initiate level shipset sequence; standard work; multi-function worker
- Form: pull from sanders; PM; reduce handling; better machine layout
- Hand work: standard work; multi-function worker
- Tank line: pull from hand work; PM; mistake proofing
- Paint: pull from tank line
- Finish: pull from paint; standard work
- P6: reduce inventory; change role to safety stock and vendor stores
- Shop flow: reduce WIP to minimum level needed for processing and handling, which in turn reduces flow time, tracking activities, and carrying costs; shift inventory to a buffer after the mills
- Material handling: increase crane responsiveness; have machinists operate cranes
- Scheduling/tracking: schedule shipsets; fixed leveled sequence with no leapfrogging; simplify tracking through visual control of WIP
- Metrics: process-oriented, such as quality, flow time, process variation, total cost
- Maintenance: Rigorous PM; must increase trust between production and maintenance organizations

Comparison of Process Flow Diagrams

Figure 3.14 compares the process flow shown at the beginning of this chapter to a new one which shows the effect of the TPS recommendations. Notice that triangles representing WIP are reduced in number and size, except for the one after the mills. Notice also that the flow in the form area is simplified. Internal push signals (straight arrows) are replaced by pull linkages (curved arrows). The new flow out of the shop passes by the P6

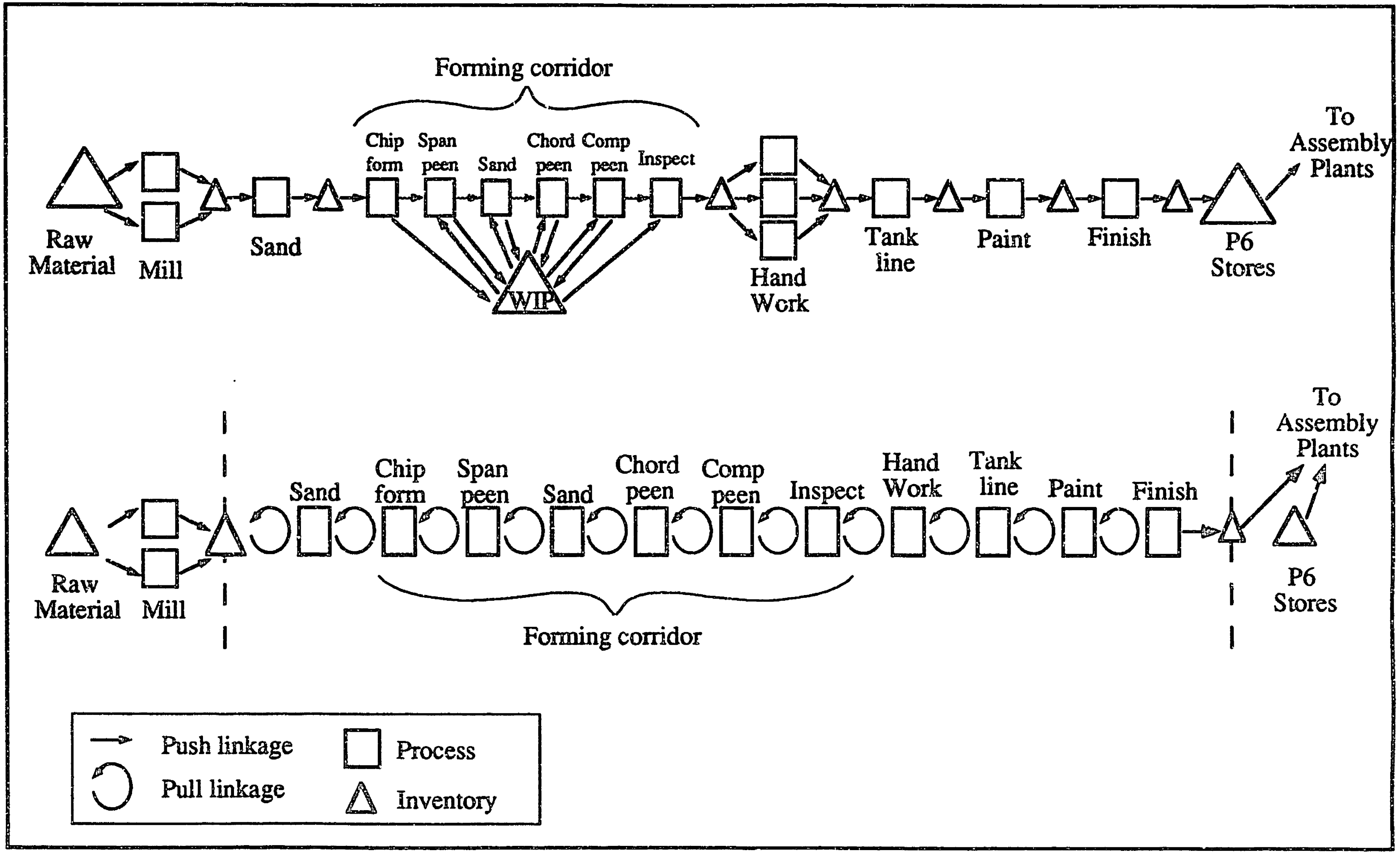

Figure 3.14 Comparison of current and proposed process flows

triangle rather than into it, representing that non-panel components are picked up from P6 while panels go straight on to the assembly plant.

Benefits of the TPS Process

The benefits offered by the TPS recommendations are many. A partial list follows:

- Process variation reduction improves panel conformance quality, reducing rework and scrap
- Increased machine uptime (a benefit in itself) reduces worker stress and disruptions in the plant
- Standardized work leads to less rework due to more consistent work activities. It also provides job documentation which enables more consistent training
- Reduced inventories, both work-in-process and finished panels. With these reductions are associated inventory carrying cost savings, which will become increasingly important to the fabrication shop managers since Boeing finance is beginning to charge shops for their inventory carrying costs
- With reduced inventory comes reduced flow time, making the plant more responsive to rate changes and less susceptible to having obsolete panels after engineering changes
- Floor space also will open up as WIP is reduced, allowing further improvements in plant layout
- Fixed sequence scheduling prevents panels from being neglected, reducing the need for constant expediting
- Shortened flow time allows AOG and other special panels to be scheduled into the regular sequence, reducing the need for special expediting
- Pull system provides smoother flow and reduces the waste of redundant handling

The benefits cited cannot be quantified until after the TPS system is in place. Some benefits, however, can be estimated. I chose to estimate the flow time and inventory reduction made possible by implementing the TPS recommendations presented in this thesis (a first-cut analysis is presented in the next chapter.)

IMPLEMENTATION PLAN

Some TPS-related conclusions, recommendations, and expected benefits have been presented. But what is needed to make this change possible? Following are recommendations for implementing these ideas and for ensuring their success. This is a plant-specific plan, different from the general plan presented in the previous chapter.

There is significant ground work which must first be completed before implementing the TPS recommendations. This groundwork includes training, creating a sense of crisis, and motivating employees to value improvement. This shop has intelligent employees who want to do a good job, and some of whom already understand the basic ideas of JIT. But until proper incentives are introduced to reward quality improvements and flow reduction, the change likely won't happen.

Before developing a level schedule, and especially before implementing pull linkages, process reliability must be improved through variation reduction and machine availability improvements. Some JIT advisors say that quality-at-the-source and JIT must be implemented simultaneously.[34] It is certainly debatable whether the two must in fact

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[34] Richard Schonberger, World Class Manufacturing. (New York: The Free Press, 1986) p201-3.

be implemented simultaneously, but it's clear that JIT certainly cannot be implemented first. JIT prerequisites include reliable quality, reduced setup time, and improved material flow. The general implementation process, then, is (1) lay foundation, (2) improve process, (3) implement pull.

Foundation

Preparing the foundation includes planning, sharing a vision of the plant's future, training, and incentives.

Plan Implementation Details

One of Toyota's strengths is lengthy, detailed up-front planning, and careful consideration of the fit between actions and company goals. A cross-functional team of managers, engineers, and shop workers should be trained in JIT ideas. Then they can study the shop, and develop their own implementation plan (hopefully with this thesis as a guide). An advisor experienced in TPS/JIT implementation should be brought in up-front to act as a guide in this planning stage and for periodic checks on the actual implementation efforts.

Share the Vision

The first step involving the entire work force should be sharing of the implementation team's vision for the plant's future. Some of this can be done through building dissatisfaction with current conditions, and some through training. Getting worker buy-in may be an obstacle greater than corporate finance or process improvement. How it's presented to the shop is critical and something the team would have to discern.

"... superimposing lean-production methods on existing mass-production systems causes great pain and dislocation. In the absence of a crisis threatening the very survival of the company, only limited progress seems to be possible."[35] This sobering observation may be overstated, but it certainly gives pause to ambitious implementation goals. It points out the need to change employee perceptions about their business. The shop (and Boeing) may need to create a sense of crisis to motivate employees to value improvement.

Boeing's CQI (Continuous Quality Improvement) program was initiated in 1986. It has been around long enough to gain some credibility and is a suitable vehicle through which to build a vision and to implement these ideas. Introducing a new program to *replace* CQI could engender cynicism in workers who predicted CQI would never catch on.

Provide Incentives and Training

Once a vision is understood and a desire to change is developed, there must be an environment supportive of the change sought. This environment includes incentives and training. Until incentives are aligned with the desired changes, the change will not occur. Managers need measurements and incentives by which to direct workers, and workers need incentives to put forth the added effort and to accept change. Proper incentives can even motivate those who don't understand or accept the vision.

Incentives may reinforce desire, but training is needed to provide clear guidance of how to act on the vision. Managers, engineers, and workers must be trained in TPS concepts, though the exact training focus would vary for the different groups. Everyone should learn the concepts and philosophy. Managers should also learn how to teach and

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[35] James P. Womack, Daniel T. Jones, and Daniel Roos, *The Machine that Changed the World* (New York: Rawson Associates, 1990) p12.

motivate them, while workers and engineers should focus on the mechanics such as setup time reduction techniques.

Process Improvement

Before a level sequence or pull system can be reliably implemented, the manufacturing process must be flexible, with little process variation. This effort is not a short-lived one---it will take a long time, likely a couple years of constant effort. A great aspect of this activity is that it helps the plant's flexibility and reliability regardless of whether JIT is finally implemented.

Reduce Process Variation

The types of variation which must be reduced are variation in machine availability and performance, variation in processing times, variation in process parameters, and variation in the resulting product characteristics. Before the process can be controlled, it must be measured, which requires new I.E. practices and process-oriented metrics.

Improvement activities fall into several areas: preventive maintenance to improve machine availability; feedback of quality control information for improved quality; as well as process control and standard work to improve quality and reduce process time variations. There are others, but these are the essential ones. Reduced variation in processing time will result in reduced idle time. These efforts would likely reduce average processing times as well, further reducing overall flow time.

A new role must be assumed by the Quality Assurance department. Inspectors must track inspection data and share it with workers. This feedback will enable employees to participate in process improvement and scrap/rework reduction efforts. The Propulsion

System Division assembly shop is making great progress in this area; for example, quality problem pareto charts are posted at each work station. Workers and supervisors also should begin visiting the assembly plants to talk to their customers.

The engineering departments also have new roles and activities to assume. Manufacturing engineering needs to more closely monitor process performance and take a more active role in process optimization. Of course this requires buy-in and support from the workers and manufacturing managers. Industrial Engineering also should develop new work standards and track performance improvements.

The maintenance department's role also must change, as discussed previously. Machine availability must be increased to provide stability for the pull system.

Increase Flexibility

Flexibility is increased through reduced setup time, reduced lot size, and improved logistics. Setup time reduction was discussed earlier for the mills and chord-wise peening machine. Setup time reduction efforts would also benefit activities as seemingly mundane as attachment of panels to the peening carriers and tank line rail carriers, or placing panels on the contour check fixtures. Lot size reduction is applicable only on the mills and has been addressed.

Necessary logistical improvements include quicker crane hookup, quicker transfer of panels on the mills, and reduction in the number of crane moves through better plant layout. The forming area's overhead rail system must also be improved to allow quicker handling of panels there.

The plant's expediters likely have a wealth of information on how to improve flow, since they know how to get a panel through the shop in two days when necessary. Use their methods and ideas when designing the new system. For example, if expediters always bypass certain paperwork, then maybe that activity isn't really needed or could be accomplished in a way that doesn't interfere with the flow. Of course, there are some expediting practices which are terribly disruptive such as stopping in-process machines, so these would not be adopted. Expediting has become institutionalized at Boeing, so asking them to help eliminate their own function would be difficult to accomplish. But if their knowledge was incorporated to help the system flow more smoothly, the whole company would benefit.

Starting Pull System

There are three aspects to establishing this pull system: synchronizing the processes, leveling the processing sequence, and reducing work-in-process (WIP). In what order should these be implemented? WIP can reduced first, but not much, for a lack of WIP will cause operations to be starved for panels. When this level of WIP is reached, then introduce the leveled sequence, then reduce WIP further. As the WIP level reaches its lower limit of that needed to absorb remaining process variation, then begin the pull linkages (synchronize). Note that inventory reduction efforts should begin with WIP, not P6 inventory. Until the plant has its new system running smoothly (a few years from now), it might be reasonable temporarily increase P6 inventory to protect the assembly plants against possible errors in the shop's TPS implementation program.

To simplify implementation, the operations can be de-coupled by breaking the shop into three sections: milling, processing from sand to finish, and P6. The two in-house sections can pursue improvement independently, de-coupled by the buffer: the mills work on lot size reduction, while the other processes reduce variation and WIP. P6 improvement comes last, when the plant has its pull system under control. Each of the three areas requires a different implementation plan, and these are presented next.

Milling

To decouple the mills from the rest of the plant, build up a buffer inventory of milled panels in front of the sanders, from which the sanders will pull panels in the fixed sequence. Since lot sizes are currently six to twenty panels, that would be a huge inventory of almost 200 panels. To reduce this buffer, the mill lot size must be reduced, which requires setup time reduction. As the lot sizes are reduced to one bed full, the buffer would be cut to 70 panels (calculation presented in the next chapter). With further improvements to lot size of one, the mills could eventually be almost fully synchronized with the rest of the shop, nearly eliminating the buffer. Only *almost* synchronized, because even with lot size of one, certain combinations of panels that are most appropriate for the mills (such as mirrored pairs, discussed earlier) and would thus come off the mill together, may not be needed at the same time for the sanders' sequence.

Actually, the buffer wouldn't be needed until the post-mill processes started using a level sequence. And that wouldn't happen until their WIP was reduced a bit and their process variation under control, which would take a year or two. Thus, if setup time and lot size reduction were begun now, the mills could be down to single-bed lot sizes before the buffer was implemented.

As the lot size is reduced, the amount of raw material (RM) needed in stock is reduced, though the total RM consumption, of course, isn't affected. When running large lots, the RM can be reduced only by keeping fewer different types of panels on hand. But when lot size is reduced, all the different panels must be kept on hand, but fewer of each type are needed at any one time. Thus, RM reduction will require delivery of smaller lots, likely with a higher frequency.

The issue of RM reduction touches on areas outside the plant walls, and possibly beyond the plant's control: purchasing contracts, transportation contracts, Alcoa's ability to produce small lots, timeliness of shipping cross-county, etc. Due to this complication, RM reduction is one of last areas in which to pursue significant change. The plant should improve its internal operations before pressuring vendors for change.

Sanding to Finishing Processes

As machine reliability is improved and process variation reduced, the WIP can be gradually reduced on all the processes at once. Eventually the lack of sequence leveling will impede further reductions because of to variation in process demands. This is when the fixed level sequence should be introduced. The sanders will stop processing panels based on priority and begin processing them based on the leveled sequence. At this point, the mills will need to have established their buffer described above. As the panels move from the sanders through the plant, they will remain in the fixed sequence.

After a couple months of running on the leveled sequence, the priority-based WIP will all be replaced by the level-scheduled WIP. At this point, the levelness should allow further WIP reductions. First place visible counters at each WIP location to show the number of panels there. Then set target levels for each WIP location, an amount which can fit into one or two standard racks. Gradually reduce the WIP to this target. Pull out all the unused WIP racks and rearrange the remaining ones so they are located near the point of production, that is, so the WIP after sanding is near the sanders, etc.

With the level sequence in use and excessive WIP eliminated, it is now time to start using pull signals and synchronize the plant. Hold each WIP location to within fixed minimum and maximum numbers of panels. This could be called a buffered pull system. Pace this pull system to whatever the bottleneck operation is at that time; a manual process such as hand work would be the best bottleneck, because its capacity can be simply varied by changing its staffing level. There are two process linkages can not become simple pull signals: the first of these is the link after the bottleneck operation, for the bottleneck pushes parts out to set the plant's pace. The second is the finishing operation which pushes finished parts to P6. Ideally, the finishing operation would set the pace, being the only push linkage, leaving the rest of the plant to use pull linkages.

The next step is to gradually reduce all the WIP buffers to the minimum allowed by each process. The actual minimum number required in each buffer is a function of the remaining process variation which could not yet be removed: variation in the imperfectly leveled sequence, machine variations, etc. Reducing the WIP further will starve some operations, which is acceptable as long as the bottleneck operation is not starved. The remaining process variation can be somewhat offset by moving workers between operations throughout the day---multi-function workers. The eventual buffer sizes will likely all be different, with larger ones before more troublesome operations. But continuous improvement can still drive them further down in the long run.

P6

The P6 warehouse is not involved in the shop's pull system. But once the shop has its pull system in place, P6 can be relegated to a role of safety stock and vendor part consolidation. As discussed earlier, if the level sequence is arranged by shipsets, then the skin and spar shop can deliver directly to the assembly plants. Also, as the shop's reliability is proven over time, the size of P6's safety stock can be reduced.

EPILOG: ACTUAL TPS EFFORTS

If the discussion thus far has implied that the shop is not trying to improve, let me assure you it is trying. This section presents some of the recent operational changes and improvements carried out in the shop. These changes demonstrate that the shop has recognized some of the benefits offered by TPS and related ideas. Their motivation, though, is not necessarily to implement TPS concepts, but to implement what they see as modern operations management methods, some of which are compatible with TPS.

Shop flow time was cut from 50 days in early 1990 to 40 days by mid-1991. According to the I.E. department, this was due in part to cutting mill lot size and part to a concerted effort to reduce flow time. A Total Productive Maintenance council was formed in the Summer of 1991 to improve machine maintenance. To reduce setup time on the mills, new seal grooves are being cut to allow using common grooves as much as possible.

When I presented my thesis findings to the Skin and Spar shop management, they said that to implement the plan they need: (1) more appropriate metrics, (2) higher priority on maintenance funds, and (3) an outside consultant to help in planning and implementation.

7-Year Vision

As part of Boeing's management process, each fabrication plant prepared a statement of its 7-year vision and an action plan. The skin and spar shop's plan emphasizes the role of CQI at all employee levels, improved process control, a shift in focus from problem detection to prevention, customer contact, JIT, and TPM. The specific goals cited are to cut flow time by two-thirds and to double inventory turn rates. While not stated in the memo, an I.E. said that another goal was to eliminate inspection.

New Frederickson Shop

Because of increased assembly plant rates and introduction of the new 777 airplane in 1994, the current skin and spar shop had insufficient capacity. Rather than expand the current shop, Boeing decided to build a second one. This project, costing several hundred-million dollars, has the following differences from the current shop:

- It is located further from the assembly plants.
- Flow time of panels through the shop is planned to be 10 days, as opposed to the current 40 days.
- WIP between processes will be processed FIFO (First Into the inventory is the First Out to the next process). But the first panel into a process is not necessarily the first out, due to different processing times. This is a more structured flow than in the current shop, but less structured than the TPS system.
- The floor plan has less room for storing WIP.
- Larger, more flexible skin mills will be used, with three spindles rather than two.
- Mill lot size will be one bed full, but the larger mills will result in larger one-bed lots.
- Mill beds will use common gasket grooves to reduce setup time.
- Touch up compression peening will be done by a robot rather than in the hand work process.

The two skin and spar shops will divide the production as follows: Auburn will process 737 panels, most lower skins, all webs, all spar chords and some stringers.

Frederickson will process all 777 skins, most upper skins, and most stringers. The P6 warehouse will be moved to the new plant.

DESIGNING A NEW PLANT

This section presents ideas for the design of a completely new skin and spar shop based on TPS concepts. The suggested approach is different from the one being pursued at the new Frederickson shop. This exercise is difficult to back up with facts---it is a hypothesis of how I think a Toyota manufacturing engineer might design the plant.

Toyota Door Manufacturing

Toyota insists on stamping all of its major sheet metal components in a stamping facility adjacent to each assembly plant. They see several advantages to having the facility on-site: better quality control, quicker response to problems, lower inventory, no shipping costs, all resulting in a much lower manufacturing cost. Toyota also assembles car doors in each assembly plant, whereas U.S. automobile manufacturers traditionally produce them in a central facility that supplies three or four assembly plants. These different scenarios (in combination with other philosophical differences) result in vastly different production processes and capital equipment requirements. One of Toyota's door lines costs about one-third as much as a GM door line, so Toyota can have three lines for GM's one, making it cost-effective to put a door line in each plant. Add to this the differences in inventory levels, shipping containers, transportation costs, and the benefit of having door quality under the assembly plant's direct control, and the advantage of Toyota's system becomes clear.

Applied to Boeing

Toyota manufactures sheet metal and doors in-house to control quality, ensure body structure integrity, and reduce costs. If these same goals are applied to the skin and spar manufacturing process, the same in-house fabrication approach results. That is, there are benefits to building a small skin and spar shop adjacent to an assembly plant. Some of the motivations and benefits follow:

- Boeing has out-sourced fuselages, systems, almost every component except the wings. For various reasons Boeing may never be able to manufacture the whole body on site as Toyota does, but the corporate strategy seems to be that they will never out-source the wings.
- Rigorous PM and process standardization reduce the need for equipment experts at each assembly plant, weakening the argument that centralization is needed for this level of process technology.
- In order to keep leading technology centralized, one of the shops can be designated as the research center, designed with increased flexibility.
- It is speculated that the next Boeing airplane will be built outside the Puget Sound area. Increased transportation distances increase the cost of a centralized manufacturing strategy.
- The increased number of shops would make the whole system more robust and allow one shop to cover for another.
- The amount of capital needed corporate-wide would not be significantly effected: there might be more peening machines and mills, but this would be determined by the type of machines employed. There would be the same number of tooling fixtures since in either case one is needed for each different part. Total inventories would be

significantly reduced. There would be no need for a central P6 warehouse, so the number of transport trucks could be reduced. Some trucks would be kept for when one plant has to cover for another, and for transporting vendor parts.

For the reasons just cited, a skin and spar shop adjacent to and dedicated to one assembly plant seems logical, given TPS ideology. Such a plant might have the following characteristics:

- Must keep cost low, reliability and flexibility high
- Must have ability to manufacture all wing components on site: skins, webs, stringers, and cords
- Small, simple, flexible machines---add more of them as rate increases[36]
- Tape, tool, and panel tryouts performed at the central plant, not at each plant
- Pull system directly synchronized to the assembly line
- Flexibility through quick setup for lot size of one
- Multi-function workers perform manual tasks (sanding, hand work, and finishing operations) in a combined area
- One flexible machine to do all peening, with quick-change peening media
- Small tank line (this may be the toughest operation to justify doing at the assembly plant because of the cost and environmental impact)

Such a decentralization strategy would require new engineering approaches to process and equipment design, similar to what Toyota has done with its door lines. The idea of decentralizing fabrication can be extended to other components, such as the flight deck and engine strut. Follow-up research should investigate what level of on-site vertical integration provides the most effective application of TPS.

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[36] Schonberger, p80-5.

CONCLUSIONS

The basic conclusions of this study, reiterated, are:

- TPS has significant applicability in this shop
- Skin panel fabrication should be thought of as a flow process rather than a job shop
- TPS has the potential to significantly reduce inventory and flow time in this shop

CHAPTER 4

WING SKINS ANALYSIS

The previous chapter discussed the applicability of TPS concepts to the skin and spar shop. Whereas it discussed inventory reduction in general terms, this chapter presents required process improvements and estimated quantitative benefits of such improvements. Data on current inventory and flow time are presented first, followed by observations on what these data indicate about the current manufacturing system. After a recap of the proposal for synchronizing the shop, a TPS-based model is presented for determining new inventory levels and flow time. The actual calculations and presented, and the resulting new inventory levels and flow time are compared to current performance, in aggregate, and specifically for the 767 airplane. This comparison will demonstrate the potential benefits of changing the plant's operation to a synchronous shipset process as described in the previous chapter.

HISTORICAL INVENTORY AND FLOW TIME

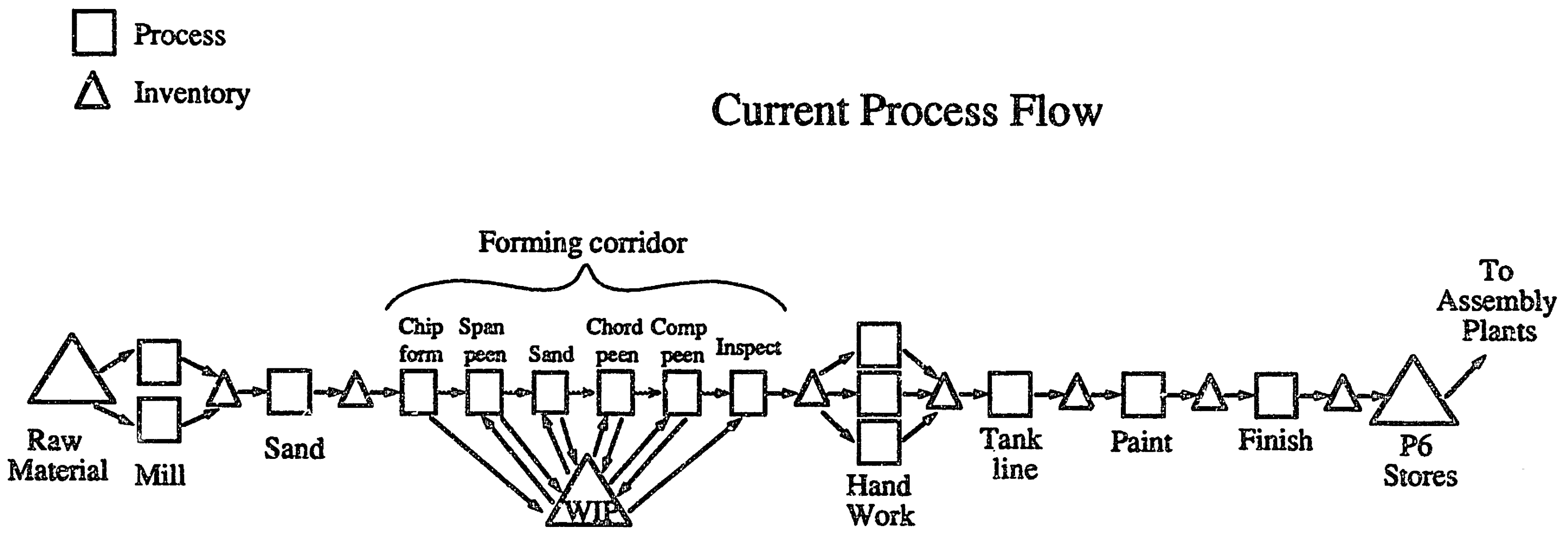
This section presents summary information on the current inventory and flow time for wing skins panels.

Flow time Total flow time includes raw material storage, processing through the shop, storage in the finished panel warehouse (P6), and time at the assembly plant. The shop currently keeps three to four months of raw material on hand. The average processing time through the shop (from milling to finishing) is about forty manufacturing days, or two months. The total flow time from when a raw material panel is received at the skin and spar shop until it flies away as part of a finished airplane is about nine months.

Because of the plant's priority scheduling, a given panel can vary widely in flow time. For example, figure 4.16 at the end of this chapter shows that among a sample of eight 767 lower #3 skin panels, processing time varied from 12 to 56 days. Simpler panels tend to flow through the shop faster than more complex panels. For example, 737 panels take only about 13 days, compared to the shop average of 40 days.

WIP An internal plant report showed production of 350 panels/month in early 1990, and about 300 panels/month in mid-1991. Based on this production rate, the planned raw material inventory would be about 1000 panels (300 panels/month * 3.5 months), but is actually a little less. The two-month flow time through the shop results in Work-In-Process (WIP) of about two months' production, or 600 panels. Since the skin mills currently run batches of about one month's production, there are approximately two batches in the system for each different panel.

Internal reports and output from the shop scheduling system allowed construction of the following summary of current inventory levels. Note that these are actual inventory levels on a single given day, not averages or targets; the actual quantities of panels will vary over time. Figure 4.1 shows the current process flow along with inventory levels and flow days at each operation. The actual flow days assume a production rate of 300 panels/month . The planned flow days data is what the Industrial Engineering (I.E.) department uses for planning production. Figure 4.2 shows a snapshot of the current inventory by airplane, panel type, and stage in the manufacturing process (Note that entries



	Raw material	Mill	Sand	Forming corridor	Hand work	Tank line	Paint/finish	P6 Stores	Total
Actual inventory (panels)	767	80	78	147	82	68	69	300	1591
Actual flow days	55	6	5	10	6	5	5	21	113
Planned flow days	73	17	6	6	6	1	4	15	128

Figure 4.1 Snapshot of wing skin panel inventories, by stage in process

Panel	Raw Material		Work in Process			Finished panels in P6		
	Left	Right	Left	Right	Shipsets	Left	Right	Shipsets
767 rear spar web	22		9	9	1	5	4	4
767 front spar web	4		14	12		5	6	
767 upper #1	16		9	10		6	5	
767 upper #2	40		3	1		8	5	
767 lower #4	16		12	10		7	8	
767 lower #1	17		14	12		6	8	
767 lower #2	3		18	19		8	5	
767 lower #3	19		12	15		7	7	
757 upper #1	9	10	20	20	15	14	10	10
757 upper #2	16	9	20	20		12	10	
757 lower #1	19		17	15		11	15	
757 lower #2	11		18	18		12	12	
757 lower #3	19		23	25		11	13	
747 rear spar web	5		6	7	5	5	5	5
747 front spar web	36		8	8		7	6	
747 upper #1	13		7	5		5	7	
747 upper #2	19		14	14		5	5	
747 lower #1	39		10	10		8	9	
747 lower #2	24		8	9		8	8	
747 lower #3	20		8	10		8	7	
747 mid spar web	35		10	9		5	6	
737 upper #2	117		37	30	30	30	40	21
737 upper #1	39		46	43		22	21	

Figure 4.2 Snapshot of wing skin panel inventories, by panel

under Raw Material that have only the left hand side listed use the same raw panel for both left and right hand finished parts.)

Observations About Current Inventory Levels

Much can be learned about the current production system by studying a detailed report of the WIP at a given point in time. Though the average WIP level is two months' worth , figure 4.2 shows that the actual WIP level varies widely between part numbers. The P6 finished panel inventory supplies the assembly plant and carries safety stock to cover for disruptions in the skin and spar shop. The column labeled "Shipsets" under "Finished Panels in P6" shows that the FGI is sufficient to supply the assembly plants for about a month. But the RM and WIP are less balanced (for example, 767 upper #2 is high in RM but low in WIP).

Carrying high levels of wing skin inventory is expensive in terms of carrying costs (opportunity cost of capital, warehouse, storage and maintenance, obsolescence, etc.). P6 is an expensive insurance policy, one which doesn't offer much protection if the FGI is out of balance (that is, if one type of panel is short, resulting in few shipsets despite high total inventory). Some might argue that the wing skin inventory is not a safety net at all, that it exists only because the shop can't produce JIT. Whether the inventory is for insurance or is an unfortunate necessity of the current manufacturing process, the following proposal addresses both issues. This proposal offers a different type of insurance policy, an investment in process reliability rather than investment in inventory to protect against accepted unreliability. The proposal suggests that a new TPS-based management framework can reduce both inventory levels and imbalances in the safety stock.

TOWARD A JIT PROCESS

As discussed in the previous chapter, the TPS goal of leveling leads to mixed model production as opposed to batching; the goal of small lots leads to 1-piece flow; the goal of zero defects leads to standard processes and process control; and a pull system leads to the elimination of buffers. To apply these ideas to the wing skin manufacturing process, it is appropriate to analyze the process in terms of to a mixed-model assembly line. Of course this shop does not have an actual assembly line, but the shop is a series of discrete processes through which all the parts flow---the sequence seldom changes, and most parts go through all the sub-processes. This similarity in process plan is much like an assembly line. The plant is already mixed-model, in that many different part numbers go through the shop in basically 1-piece flow; that is, any operation can run the parts in any order it likes (though priority is the major influence on actual sequence).

The comparison to an assembly line currently breaks down in two areas: (1) how the wing skins are constantly leapfrogging through the shop, and (2) the excessive amount of buffer inventory. "Leapfrogging" refers to fact that the sequence in which a sub-process (ex. hand work) processes panels has little correlation to the sequence in which the panels arrived. The last panel in could be first out, last out, anywhere in the sequence. And regarding buffers, most assembly lines have some slack in the line, but not to the extent that this shop has.

This understanding of the similarities to and differences from an assembly line allows discretionary application of assembly line improvement methods. The amount of slack and excess WIP in an assembly line can be reduced through traditional I.E. time and motion study methods, by process variation reduction, or other ways. And in mixed model lines, improved sequencing can further reduce the need for buffers. Applying Toyota's assembly line improvement methods to this plant led to the following recommended improvement plan:

1. Reduce process variation Required before synchronizing, will improve quality and eliminate waste as well
2. Synchronize Work toward a steady processing rate
3. Level-schedule Develop a fixed sequence for running panels which levels demand on resources and simplifies process planning
4. Reduce WIP Reduced process variation and leveled schedule reduce the need for idle buffer WIP
5. Reduce flow Automatic, since WIP level determines flow time
6. Start pull system With reduced WIP and flow time, visual control can be used to tighten the control loop

The rest of this chapter further develops this six-step improvement plan and presents analysis intended to estimate the resulting benefits.

Reduce Variation in Processing Times

Before a level sequence can be consistently maintained, the process must be in control, with variation significantly reduced. This thesis is concerned primarily with reduced variation in actual processing time for a given panel in a given process (ex. sanding of 767 upper #1). Reducing variation in process parameters and resulting product characteristics is also required for implementing my recommendations, but such improvements are not quantified in this analysis.

Once variation is reduced, the average processing times can be taken as fixed (or nearly so) to develop a leveled schedule. This analysis assumes such variation reduction has been performed and that the remaining variation is negligible. Since neither I nor Boeing I.E. has accurate information on actual processing times, labor hour information is used in the analysis. Labor hours are closely related to actual processing times for manual processes (sanding and hand work) but not for the others. Using labor hours allows demonstration of the analytical process, though it taints the realism of the results. Before implementing this thesis' recommendations, the shop must collect actual processing time data and determine a new sequence.

Since this model is to demonstrate the benefits of reducing variation, it assumes no reduction in average processing time---just reduction in variation. However, efforts to reduce variation would likely reduce waste, reducing actual processing times as well.

Synchronize

Synchronizing the plant, as if it were an assembly line, requires a line speed. Toyota describes the inverse of line speed as "takt time," which is the time interval between individual jobs on the line. For example, a line speed of 60 jobs per hour gives a takt time of one minute. This plant's monthly production requirements are shown in figure 4.3. This table and the following analysis use approximate line rates. Since the actual line rates change occasionally, any rates used would soon become obsolete, and so would the calculations based upon them. A rate change would not affect the analytical method, but a new processing sequence would have to be developed.

The monthly demand of 40 airplanes per month translates to two airplanes per day (one 737 and one other) or 350 panels and spar webs per month. According to Boeing I.E., available production time is 21.51 hours/day (running three shifts), and an average month has 20.75 manufacturing days. This gives a takt time of 1.275 hours, meaning the plant's "assembly line" advances once every 1.275 hours (Fig 4.4).

Airplane	Shipsets /Month	Panels/ Shipset	Panels /Month
737	20	4	80
747	5	18	90
757	10	10	100
767	5	16	80
	Total	**Panels/Month**	**350**

Figure 4.3 Airplane production rates used in the model

$$Takt = \frac{21.51\frac{Hours}{Day} * 20.75\frac{Days}{Month}}{350\frac{Panels}{Month}} = 1.275\frac{Hours}{Panel}$$

Figure 4.4 Calculation of Takt Time

Significance of Sequencing

Improved scheduling can reduce the need for buffer WIP. Before presenting development of the fixed sequence, some general ideas on sequencing are presented.

Sequencing a single operation Assume a single worker has to process six parts each day, and there are two types of parts, some taking a half-hour, the others taking two hours. Clearly, giving six hard parts one day and six easy parts the next day would be an uneven use of resources. One way to smooth out the work would be to run three easy parts followed by three hard parts, or vice-versa. Another is to alternate easy and hard parts. For this single operator, the sequence wouldn't matter as long as each day had the same total amount of work.

Sequencing two operations Now suppose that when the parts left this operation, they went to a second one where the complexity was reversed. That is, the part which required only a half-hour for the first operation requires two hours for the second, and vice-versa. If the first operator runs three hard parts followed by three easy parts, once the cycle got going, both operators would process six parts in a day, but there would be idle WIP. Figure 4.5 illustrates this. The arrows represent part transfer from first to second operator. A diagonal arrow shows that the part is idle while waiting for the second operator.

The second operator can influence the total amount of idle time by the way she decides which part to process next from WIP. If she always processes the oldest part (FIFO) then the total idle time per day is 9 part*hours. But if she wants to keep the WIP lower, she can use a 2-stage selection process: (1) chose an easy part over a hard one to get it out quicker (reduce backlog), (2) but when the WIP pieces are all the same, process the oldest one. With this 2-stage process (easiest, then oldest) the total idle time is reduced to 7.5 part*hours. But to do so, she needs a process that can easily convert between the two types of parts since she changes four times per day while first operator only changes twice per day.

Regardless of her decision criteria, the second operator cannot totally eliminate the idle WIP. But if the first operator changes the way he performs his process, WIP idleness can be totally eliminated. If the first operator can reduce his setup time to where he can alternate easy and difficult part types, then when the parts get to the second operator, she can also alternate, and idle time is eliminated.

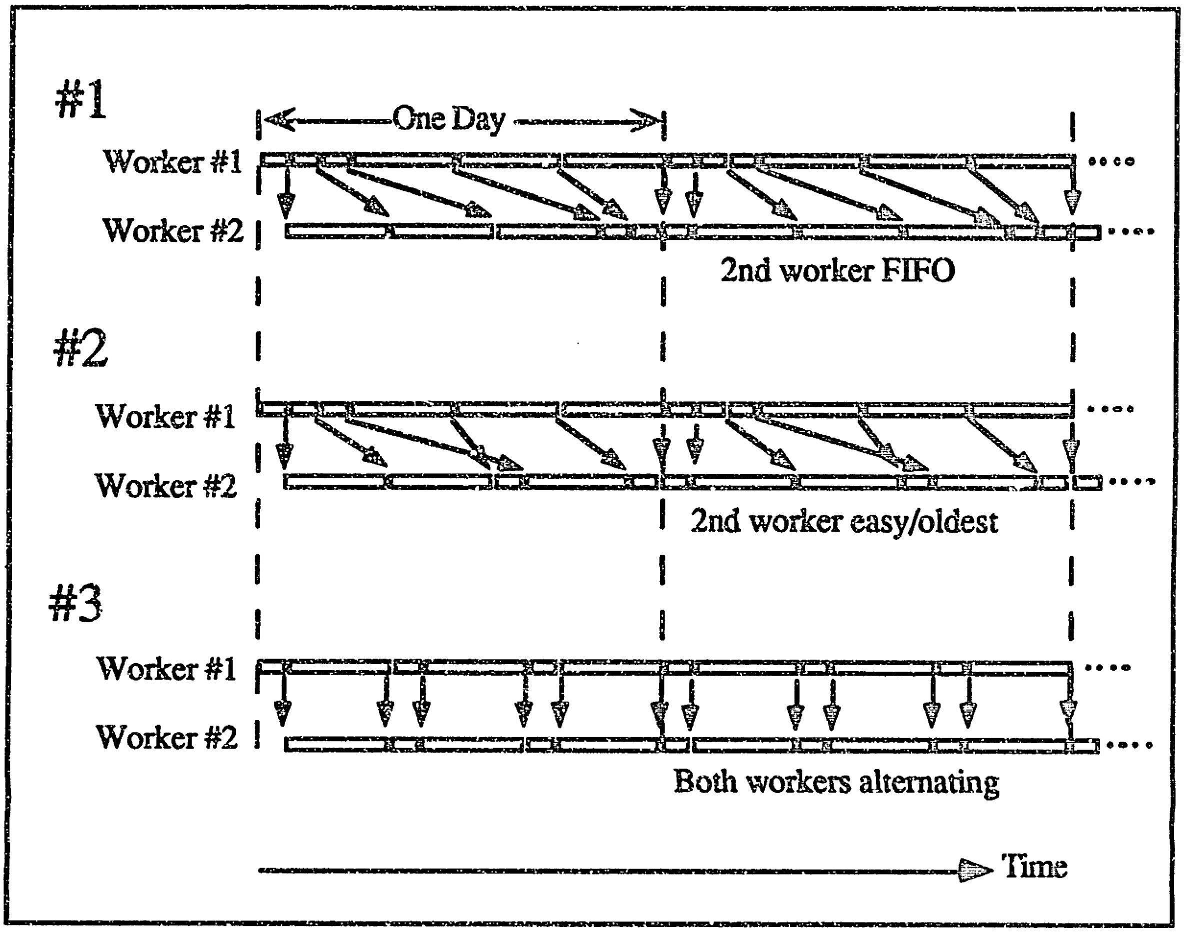


Figure 4.5 Examples of job sequencing

This simple example demonstrates how the sequence at one operation can effect the next operation. To apply this to the skin and spar shop, the model must be expanded into several stages, not just two, and it must accommodate a wide range of processing times. With the several linked processes in the skin and spar shop, sequencing is a challenge.

Free flow versus fixed sequence In developing a processing sequence for the whole shop, there are at least two approaches:

1. Job-shop approach: allow each panel to flow through the shop at its fastest possible rate, based on its required processing time
2. Assembly line approach: keep panels in a fixed sequence as they flow through the shop

Although there may be compromise solutions, this thesis considers only these two options. In either case, careful scheduling means knowing the processing sequence at each operation, and, therefore, it means beginning the panels in a predetermined sequence.

The first approach is approximately equivalent to having each operation process the easiest panel available to it at the moment. To determine the sequence would require planning the processing sequence at each step of the process, planning when panels would jump ahead in the sequence. If operators always processed the easiest panel available, there might be a tendency for WIP to accumulate or processes to be starved unless the panels were carefully sequenced. Any remaining imbalance could be controlled by limiting buffer WIP or using Kanban-type signals to advance the assembly line every takt time. Planning this processing sequence with all of its leapfrogging and shuffling would be incredibly complex. If this complexity could be handled, then planning would begin with selecting the sequence in which the panels would leave the shop. Then, based on processing times, plan the processing and leapfrogging backwards through the plant's processing stations, all the way back to the first synchronized operation (sanding) in order to determine the sequence in which the sanders should process panels in order for them to end up in the desired sequence at the end of the shop.

The second approach (fixed sequence) would not allow any leapfrogging. Panels would begin at the sanders in a predetermined sequence; as they arrived at forming they would be processed in the same sequence, on through the plant, being painted, finished, and loaded onto the P6 trailers in the same sequence they began. Though this should be much simpler to track through the plant than the first method, it may still be difficult to plan the sequence in a manner which levels the demand on all processes.

A fixed sequence seems most harmonious with TPS concepts of mixed-model processing, level scheduling, and visual control. Therefore, the remainder of this analysis proceeds with the goal of developing a level fixed sequence.

Individual panels vs. shipsets The next question is, how should this fixed sequence be developed; how can the best processing sequence be determined? As discussed in the previous chapter, TPS advocates shipset processing, which allows production to be more synchronized with the needs of the assembly plants, supporting the concept of JIT. Since P6 sends matched shipsets of panels to the assembly plant, P6 should receive matched shipsets from the shop. Therefore, the shop should finish the panels in matched shipsets. To finish the panels in matched shipsets while maintaining a fixed sequence, the panels must begin the process in matched shipsets.

Development of Level-Scheduled Fixed Shipset Sequence

The model for developing a preliminary leveled shipset schedule for the shop is admittedly crude. It is intended to provide only a first cut analysis to demonstrate the concepts. It is not a detailed I.E. model robust against random disruptions, nor does it include distributions of processing times. The reason is that the data required for such an analysis doesn't exist. Were the plant to implement this scheduling method, it would have to collect more accurate data, develop a more complete model, then determine the actual sequence. And all this could be done only after processes are standardized and process variation reduced, which would obsolete all of the data used here.

Sequence development begins with assumed monthly production rates of twenty 737s, five 747s, ten 757s, and five 767s. Figure 4.6 illustrates an idealized airplane delivery schedule for the company. The assembly plants' needs for wing panel shipsets should be the same, though time-shifted due to the assembly time.

Days in Month ——→ Time

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
737	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
747				x				x				x				x				x	
757	x		x		x		x		x		x		x		x		x		x		x
767		x				x				x				x				x			

Figure 4.6 Assumed assembly plant schedule

The JIT philosophy advocates manufacturing wing skin shipsets in the same sequence as consumed, which, again, should be the same as shown in figure 4.6, except with a time shift, since the panels must be started quite a while before they're needed in the assembly plant. This results in two shipsets being built each day: one 737 and one other. The other is a 757 half the time, and a 767 or 747 a quarter of the time each. Notice that the production schedule is a series of repeated four-day cycles, a cycle that is similar to the leveled mixed-model production of an assembly line.

At this point, specific shipsets are scheduled to be run on specific days. The next step is to determine the sequence for processing the panels within a shipset. For example, assume that it is day 1 of the month shown above, so the schedule is to build a 737 and a 757. The four 737 panels and ten 757 panels should be arranged in such a way that as they pass through the various manufacturing operations, there is minimal variation in demand on the processes. This is difficult since a given panel might have unusually high demand on one process and unusually low on another, compared to other panels in the sequence. This inconsistency of demand on processing resources requires balancing the needs and flexibilities of the various processes, to keep each processing operation satisfied with the sequence.

Process Constraints on Sequence

The specific leveling concerns of each process are described below. In general, the milling, forming, tank line, and paint processes are largely machine oriented, constrained by machine capacity and speed limitations. Changes in manpower cannot significantly alter the process speed or capacity---only process redesign or additional machines can do that. The sanding, hand work, and finish processes, on the other hand, are largely manual, so their limitations involve labor availability and utilization. The speed and capacity can be changed easily, but at a significant labor cost. More specific limitations are listed below.

Milling Setup time is a major restriction here. If lot size can be reduced to one bed full, the mills would be much more responsive, yet 1-piece flow may still not be possible.

Sanding The only restriction here is available manpower.

Forming Some panels are chip-formed, but this is a fairly quick process, imposing little restriction on the sequence. Loading skins onto the overhead carriers takes up to a couple hours, so panels requiring excessive time to load should be separated.

The amount and type of peening needed by the panels varies: all panels need compression peening; and most skin panels need chord-wise and/or span-wise peening. It would help to spread out the 747 panels since they need the least peening, but that would undermine the shipset processing goal.

Inspecting contour on non-747 skins is done on large fixtures. Because of the presence of handling tabs on the skins, two adjacent panels cannot be simultaneously loaded onto the same checking fixture. So if there are three skins to check on a given fixture, spread them out through the day's sequence so they are checked in the order 1, -, 3, -, -, -, 2 (Dashes represent panels which use other fixtures.) Since panels #1 and #3 don't interfere, they can be checked at the same time. This sequence gives extra time to get both #1 and #3 out of the way before bringing in #2. Also, alternating between left and right hand panels would prevent interference since they use separate fixtures.

Hand work Like sanding, the limiting factor here is manpower, not machine time. The webs and enclosure panels require significantly more hand work than the other panels, so they should be spread out though the sequence.

Tank line This process takes about two hours from load to unload, so there is no processing time restriction if each carrier has two panels. If more than one panel is loaded, they must be from the same alloy group due to different etching times. Thus, it would help if panels arrived presorted into alloy groups.

Paint The painting process itself is largely indifferent to sequence. But before painting enclosure panels (the ones with fuel access panel openings) the edges of the openings must be modified, which takes an hour or two. So separating the enclosure panels when possible is helpful.

Finishing The only restriction here is manpower. Since the panels all receive basically the same treatment (cut off a few tabs and treat the exposed metal), this process is largely indifferent to the sequence.

Deriving Sequence

Considering the various needs described above, the panels can be arranged in a sequence which trades off the conflicting requirements of the various operations. It is a compromise arrangement, one that seeks to optimize the plant as a whole rather than optimize the sequence for any individual process.

To determine the fixed sequence, the panels required to build one side (left or right) of a 737-7X7 pair of airplanes are listed, then arranged to smooth out the demand on resources, as measured by moving averages. This first-cut ordering was based on hand work labor hours, since this is the process which varies most in magnitude of demand. The sequencing also used sanding process time as a second measure of leveling, making compromise rearrangements to smooth out sanding without reintroducing significant variation in hand work. Hand work and sanding times were obtained from the shop scheduling computer which keeps data on the average labor hours for all panels processed in the previous year.

The 737 panels are spread throughout the other airplane's panels to prevent a backup at the 737 checking fixture. The enclosure panels and webs are also spread out to level demand on the hand workers. Figure 4.7 illustrates this initial sequences for the individual two-shipsets days.

Next, four 737-7X7 groups were put together to represent a four-day cycle, then some panels were rearranged within their days to smooth out transitions between the days (Fig. 4.8). As presented later in this chapter, the hand work operation needs seven panels in-process. Therefore, a seven-panel moving average was used to measure variation in hand work demands. That is, the panels in hand work at any instant need to have a consistent total work content, so that demand is leveled over the day. Sanding used a five-panel moving average for identical reasons. Then the sequence was further adjusted for the needs of forming, check fixtures, and paint, but only when it didn't significantly impact the moving averages for hand work and sanding. Note that the panels listed below the double divider line are the same as at the beginning of the cycle; they are repeated to see how moving averages are affected by the interface between two complete four-day cycles.

For the final sequence, the other half of each shipset was added; that is, it included both left and right hands. Basically, this was done by listing each group twice, making minor rearrangements to further smooth demand, and then selecting which of the identical panels should be left hand or right. This final decision was based on minimizing congestion at the contour check fixtures (Panels for which the sequence is indifferent to hand have LR in the "side" column.) The final sequence, along with the data on moving average and equipment demands, is shown in figure 4.9.

Analysis of Sequence Levelness

The following analysis evaluates how level this sequence really is, to test whether shipset processing actually levels demand on the plant's processes.

Regarding Leveling of Demand on Fixtures

In the final sequence chart (Fig. 4.9) the columns labeled "Other restrictions" summarize the load on form checking fixtures, layout inspection, and paint. To read the chart, scan down one of the columns; the numbers 3, 4, 5, 6 represent which airplane the

	Handwork						Sanding					
	Nom'l	--- Moving	Averages ---				Nom'l	--- Moving	Averages ---			
737-757 Set	**Hours**	**2**	**3**	**4**	**5**	**6**	**Hours**	**2**	**3**	**4**	**5**	**6**
757 Lwr #2	34.0						21.0					
737 Upr #2	3.3	18.7					3.3	12.2				
757 Upr #2	6.6	5.0	14.6				8.9	6.1	11.1			
737 Upr #1	10.2	8.4	6.7	13.5			6.3	7.6	6.2	9.9		
757 Lwr #1	18.4	14.3	11.7	9.6	14.5		8.4	7.4	7.9	6.7	9.6	
757 Upr #1	8.3	13.4	12.3	10.9	9.4	13.5	14.6	11.5	9.8	9.6	8.3	10.4
757 Lwr #3	19.8	14.1	15.5	14.2	12.7	11.1	9.8	12.2	10.9	9.8	9.6	8.6
737-767 Set												
767 Rear Web	51.2						12.3					
737 Upr #2	3.3	27.3					3.3	7.8				
767 Lwr #3	35.5	19.4	30.0				12.8	8.1	9.5			
767 Upr #2	11.0	23.3	16.6	25.3			10.2	11.5	8.8	9.7		
767 Lwr #4	12.6	11.8	19.7	15.6	22.7		11.6	10.9	11.5	9.5	10.0	
767 Lwr #2	41.3	27.0	21.6	25.1	20.7	25.8	21.5	16.6	14.4	14.0	11.9	12.0
737 Upr #1	10.2	25.8	21.4	18.8	22.1	19.0	6.3	13.9	13.1	12.4	12.5	11.0
767 Front Web	30.5	20.4	27.3	23.7	21.1	23.5	11.2	8.8	13.0	12.7	12.2	12.3
767 Upr #1	12.1	21.3	17.6	23.5	21.3	19.6	15.3	13.3	10.9	13.6	13.2	12.7
767 Lwr #1	13.2	12.7	18.6	16.5	21.5	20.0	8.2	11.8	11.6	10.3	12.5	12.4
737-747 Set												
747 Rear Web	50.4						10.8					
737 Upr #2	3.3	26.9					3.3	7.1				
747 Out Frt Web	3.9	3.6	19.2				1.0	2.2	5.0			
747 Lwr #2	38.2	21.1	15.1	24.0			32.0	16.5	12.1	11.8		
747 Upr #2	22.6	30.4	21.6	17.0	23.7		23.4	27.7	18.8	14.9	14.1	
747 Front Web	47.7	35.2	24.7	19.4	25.6	27.7	9.8	16.6	21.7	16.6	13.9	13.4
737 Upr #1	10.2	16.4	23.7	18.7	15.6	21.0	6.3	14.9	20.6	15.7	13.2	12.6
747 Mid Web	40.1	25.1	24.3	27.8	23.0	27.1	16.8	11.6	15.5	19.6	15.9	14.9
747 Lwr #3	27.5	33.8	25.9	25.1	27.7	31.0	20.1	18.5	14.4	16.7	19.7	18.1
747 Upr #1	21.2	24.4	29.6	24.7	24.3	28.2	24.1	22.1	20.3	16.8	18.1	16.8
747 Lwr #1	16.6	18.9	21.8	26.4	23.1	27.2	13.2	18.7	19.1	18.6	16.1	15.1

Figure 4.7 Initial shipset sequence, calculated separately for each day

		Handwork		**Sanding**	
		Nominal Hours	7-Panel Average	Nominal Hours	5-Panel Average
737-757 Set	757 Lwr #2	34.0		21.0	
	737 Upr #2	3.3		3.3	
	757 Upr #2	6.6		8.9	
	737 Upr #1	10.2		6.3	
	757 Lwr #1	18.4		8.4	9.6
	757 Upr #1	8.3		14.6	8.3
	757 Lwr #3	19.8	14.4	9.8	9.6
737-767 Set	767 Rear Web	51.3	16.8	12.3	10.3
	737 Upr #2	3.3	16.8	3.3	9.7
	767 Lwr #3	35.5	21.0	12.8	10.6
	767 Upr #2	11.0	21.1	10.2	9.7
	767 Lwr #1	13.2	20.3	8.2	9.4
	737 Upr #1	10.2	20.6	6.3	8.2
	767 Lwr #4	12.6	19.6	11.6	9.8
	767 Upr #1	12.1	14.0	15.3	10.3
	767 Front Web	30.5	17.9	11.2	10.5
	767 Lwr #2	41.3	18.7	21.5	13.2
737-757 Set	757 Lwr #2	34.0	22.0	21.0	16.1
	737 Upr #2	3.3	20.6	3.3	14.5
	757 Upr #2	6.6	20.1	8.9	13.2
	737 Upr #1	10.2	19.7	6.3	12.2
	757 Lwr #1	18.4	20.6	8.4	9.6
	757 Upr #1	8.3	17.4	14.6	8.3
	757 Lwr #3	19.8	14.4	9.8	9.6
737-747 Set	747 Rear Web	50.4	16.7	10.8	10.0
	737 Upr #2	3.3	16.7	3.3	9.4
	747 Outer Frt Web	3.9	16.3	1.0	7.9
	747 Lwr #2	38.2	20.3	32.0	11.4
	747 Upr #2	22.6	20.9	23.4	14.1
	737 Upr #1	10.2	21.2	6.3	13.2
	747 Mid Web	40.1	24.1	16.8	15.9
	747 Lwr #3	27.5	20.8	20.1	19.7
	747 Upr #1	21.2	23.4	24.1	18.1
	747 Lwr #1	16.6	25.2	13.2	16.1
	747 Front Web	47.7	26.6	9.8	16.8
737-757 Set	757 Lwr #2	34.0	28.2	21.0	17.6
	737 Upr #2	3.3	27.2	3.3	14.3
	757 Upr #2	6.6	22.4	8.9	11.2
	737 Upr #1	10.2	19.9	6.3	9.9
	757 Lwr #1	18.4	19.5	8.4	9.6
	757 Upr #1	8.3	18.4	14.6	8.3
	757 Lwr #3	19.8	14.4	9.8	9.6

Figure 4.8 Second sequence, four-day cycle, one side only

				Handwork		Sanding		Other restrictions					
		Sequence Number	Side	Nominal Hours	7 Panel Average	Nominal Hours	5 Panel Average	A	B	C	D	E	F
737-757 Set 1st half	757 Lwr #2	1	L	34.0	27.9						5	5	
	737 Upr #2	2	L	3.3	26.9				3				
	757 Upr #2	3	L	6.6	21.1				5				
	737 Upr #1	4	R	10.2	18.6			3					
	757 Lwr #1	5	R	18.4	18.2		9.6			5			
	757 Upr #1	6	R	8.3	17.0		8.3	5					
	757 Lwr #3	7	L	19.8	14.4	9.8	9.6				5		
737-757 Set 2nd half	757 Lwr #2	8	R	34.0	14.4	21.0	12.0			5		5	
	737 Upr #2	9	R	3.3	14.4	3.3	11.4	3					
	757 Upr #2	10	R	6.6	14.4	8.9	11.5	5					
	737 Upr #1	11	L	10.2	14.4	6.3	9.9		3				
	757 Lwr #1	12	L	18.4	14.4	8.4	9.6				5		
	757 Upr #1	13	L	8.3	14.4	14.6	8.3		5				
	757 Lwr #3	14	R	19.8	14.4	9.8	9.6			5			
737-767 Set 1st half	767 Rear Web	15	LR	51.3	16.8	12.3	10.3						6
	737 Upr #2	16	R	3.3	16.8	3.3	9.7	3					
	767 Upr #2	17	L	11.0	17.5	10.2	10.0		6				
	767 Lwr #3	18	R	35.5	21.1	12.8	9.7			6			
	767 Lwr #1	19	L	13.2	20.3	8.2	9.4				6		
	737 Upr #1	20	L	10.2	20.6	6.3	8.2		3				
	767 Front Web	21	LR	30.5	22.1	11.2	9.7						6
	767 Lwr #2	22	L	41.3	20.7	21.5	12.0				6	6	
	767 Lwr #4	23	R	12.6	22.0	11.6	11.8			6			
	767 Upr #1	24	L	12.1	22.2	15.3	13.2		6				
737-767 Set 2nd half	767 Rear Web	25	LR	51.3	24.5	12.3	14.4						6
	737 Upr #2	26	L	3.3	23.0	3.3	12.8		3				
	767 Upr #2	27	R	11.0	23.2	10.2	10.5	6					
	767 Lwr #3	28	L	35.5	23.9	12.8	10.8				6		
	767 Lwr #1	29	R	13.2	19.9	8.2	9.4			6			
	737 Upr #1	30	R	10.2	19.5	6.3	8.2	3					
	767 Front Web	31	LR	30.5	22.1	11.2	9.7						6
	767 Lwr #2	32	R	41.3	20.7	21.5	12.0			6		6	
	767 Lwr #4	33	L	12.6	22.0	11.6	11.8				6		
	767 Upr #1	34	R	12.1	22.2	15.3	13.2	6					
737-757 Set 1st half	757 Lwr #2	35	L	34.0	22.0	21.0	16.1					5	
	737 Upr #2	36	L	3.3	20.6	3.3	14.5		3				
	757 Upr #2	37	L	6.6	20.1	8.9	12.0		5				
	737 Upr #1	38	R	10.2	17.2	6.3	11.0	3					
	757 Lwr #1	39	R	18.4	13.9	8.4	9.6			5			
	757 Upr #1	40	R	8.3	13.3	14.6	8.3	5					
	757 Lwr #3	41	L	19.8	14.4	9.8	9.6				5		
737-757 Set 2nd half	757 Lwr #2	42	R	34.0	14.4	21.0	12.0			5		5	
	737 Upr #2	43	R	3.3	14.4	3.3	11.4	3					
	757 Upr #2	44	R	6.6	14.4	8.9	11.5	5					
	737 Upr #1	45	L	10.2	14.4	6.3	9.9		3				
	757 Lwr #1	46	L	18.4	14.4	8.4	9.6				5		
	757 Upr #1	47	L	8.3	14.4	14.6	8.3		5				
	757 Lwr #3	48	R	19.8	14.4	9.8	9.6			5			
737-747 Set 1st half	747 Rear Web	49	LR	50.4	16.7	10.8	10.0						4
	737 Upr #2	50	R	3.3	16.7	3.3	9.4	3					
	747 Out Frt Web	51	LR	3.9	16.3	1.0	7.9						
	747 Mid Web	52	LR	40.1	20.6	16.8	8.3						4
	747 Upr #2	53	LR	22.6	21.2	23.4	11.1						
	737 Upr #1	54	L	10.2	21.5	6.3	10.2		3				
	747 Front Web	55	LR	47.7	25.5	9.8	11.5						4
	747 Lwr #3	56	LR	27.5	22.2	20.1	15.3						
	747 Upr #1	57	LR	21.2	24.7	24.1	16.7						
	747 Lwr #1	58	LR	16.6	26.6	13.2	14.7						
	747 Out Frt Web	59	LR	3.9	21.4	1.0	13.6						
737-747 Set 2nd half	747 Rear Web	60	LR	50.4	25.4	10.8	13.8						4
	737 Upr #2	61	L	3.3	24.4	3.3	10.5		3				
	747 Lwr #2	62	LR	38.2	23.0	32.0	12.1					4	
	747 Mid Web	63	LR	40.1	24.8	16.8	12.8						4
	747 Upr #2	64	LR	22.6	25.0	23.4	17.3						
	737 Upr #1	65	R	10.2	24.1	6.3	16.4	3					
	747 Front Web	66	LR	47.7	30.4	9.8	17.7						4
	747 Lwr #3	67	LR	27.5	27.1	20.1	15.3						
	747 Upr #1	68	LR	21.2	29.6	24.1	16.7						
	747 Lwr #1	69	LR	16.6	26.6	13.2	14.7						
	747 Lwr #2	70	LR	38.2	26.3	32.0	19.8					4	
737-757 Set 1st half	*757 Lwr #2*	*1*	*L*	*34.0*	*27.9*	*21.0*	*22.1*				*5*	*5*	
	737 Upr #2	*2*	*L*	*3.3*	*26.9*	*3.3*	*18.7*		*3*				
	757 Upr #2	*3*	*L*	*6.6*	*21.1*	*8.9*	*15.7*		*5*				
	737 Upr #1	*4*	*R*	*10.2*	*18.6*	*6.3*	*14.3*	*3*					
	757 Lwr #1	*5*	*R*	*18.4*	*18.2*	*8.4*	*9.6*			*5*			
	757 Upr #1	*6*	*R*	*8.3*	*17.0*	*14.6*	*8.3*	*5*					
	757 Lwr #3	*7*	*L*	*19.8*	*14.4*	*9.8*	*9.6*				*5*		

A Upper right fixture
B Upper left fixture
C Lower right fixture
D Lower left fixture
E Enclosure panel
F Web

Figure 4.9 Final shipset sequence

panel is for, the X in 7X7. The separation of identical numbers (e.g.. the number of panels between two 5's) represents the time between successive uses of the same resource.

Contour check fixtures are used to verify the curvature of panels after being shaped in the forming operation. There are two fixture for 737: one for upper left, one for upper right. There are four checking fixtures for each of 757 and 767: upper left, upper right, lower left, lower right. Each of these fixtures has a column. (747 panels are checked while hanging, so no fixture is needed.) Because loading, checking and unloading a panel from a fixture take a couple hours, the panels which use a common fixture have been spread out.

The enclosure panels are also spread out because of the time needed for hand work and to prepare the fuel access holes before paint. The webs are also spread out because of their excessive hand work.

Some steps in the manufacturing process that call for a slightly different sequence may have been overlooked, such as some arcane aspect of the forming process. However, that this is not meant to be the ultimate sequence---it is meant to demonstrate that when the various processes coordinate their needs, a mutually accommodating compromise sequence can be derived, one that will level demand and reduce the need for buffer WIP.

Regarding Leveling of Hand Work and Sanding Time

Now for a look at the labor-intensive processes. Since Boeing performance measurement currently focuses on labor utilization, leveling the demand on labor is of significant concern. Figures 4.10 and 4.11 graph the hand work and sanding times for each panel as well as their moving averages. (The moving average represents the levelness of demand on the resource.) Notice that for hand work that the intermixing of panels with short and long processing times results in a smooth but drifting moving average. (To read the graph, the moving average value at sequence number n is the average of panels n-6 through n for hand work and n-4 through n for sanding.) The moving average trends move down for 737-757 sets and up for 737-747 and 737-767 shipsets. This is because 747 and 767 panels are significantly larger and more complex than 757 panels, so they require more work.

Sanding generally takes less time than hand work, and it varies less in magnitude. The sanding moving average displays similar trends to hand work, in that it is generally higher for 767 and 747 sets than for 757. Sanding is plotted with the same vertical scale range as hand work to better visualize the difference in levelness.

Despite the relative roughness of the moving averages, the complexity of panels is rather well distributed. If it were not for the approximate correlation between the hand work and sanding times, the moving average would likely be even rougher than it is, so the little correlation which does exist ($R^2 = 25\%$) is beneficial to leveling. See figure 4.12 for a scatter plot, regression line and residual histograms. The two outliers circled are 747 and 767 rear webs which require extensive hand work.

Impact of Variation in Moving Average

The objective of this analysis was to develop a sequence of panels that would allow the shop to run synchronized as an assembly line, with all panels advancing together every takt time, needing no buffer WIP. The moving average trends just presented impose a complication. Since the moving average value at any time represents the total amount of work in the station, when the average is high, the work content is high, requiring extra workers to keep parts flowing; and when the average is low, the work content is low, resulting in fewer workers needed. Unfortunately, this is opposed to leveling which seeks constant resource utilization rates.

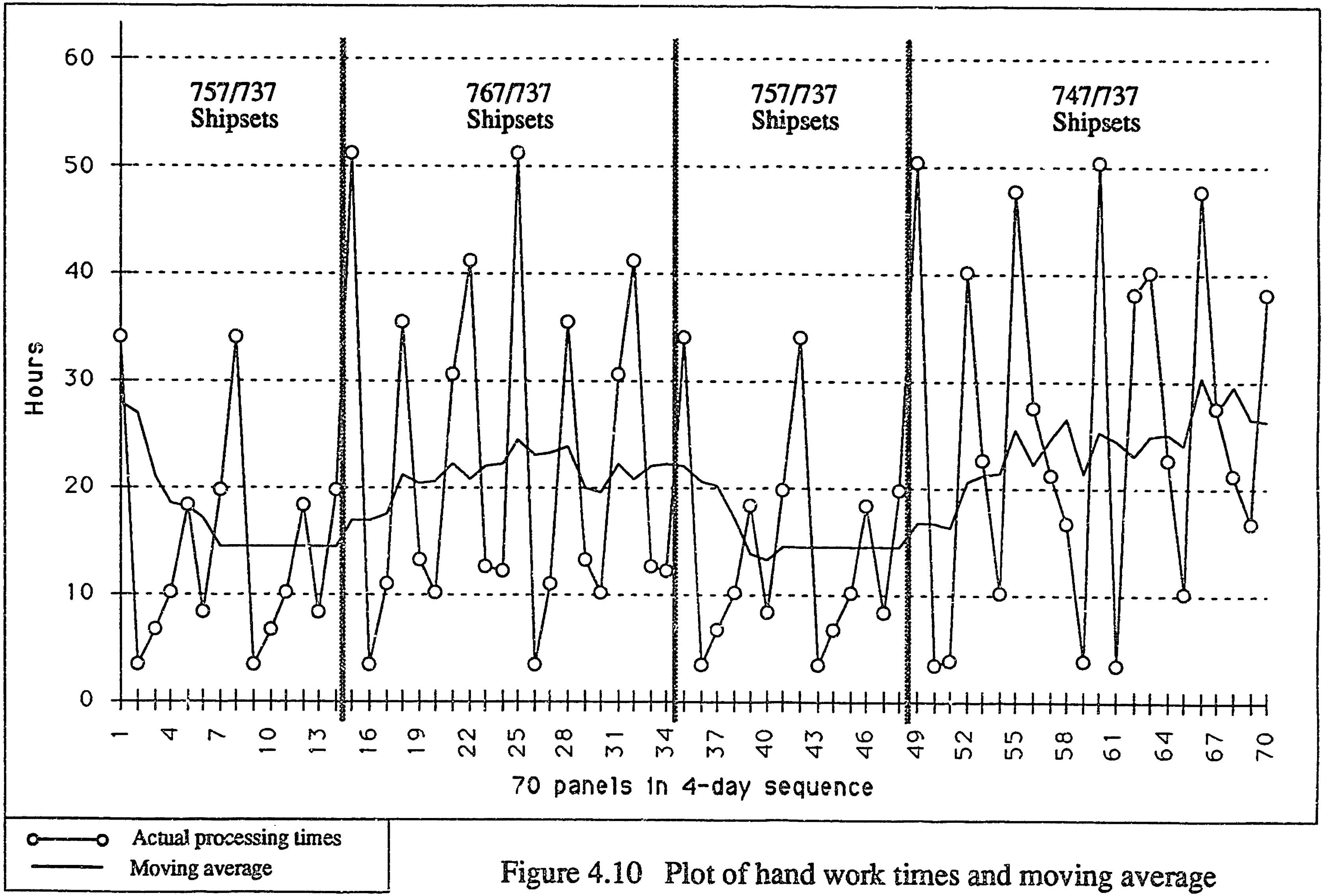


Figure 4.10 Plot of hand work times and moving average

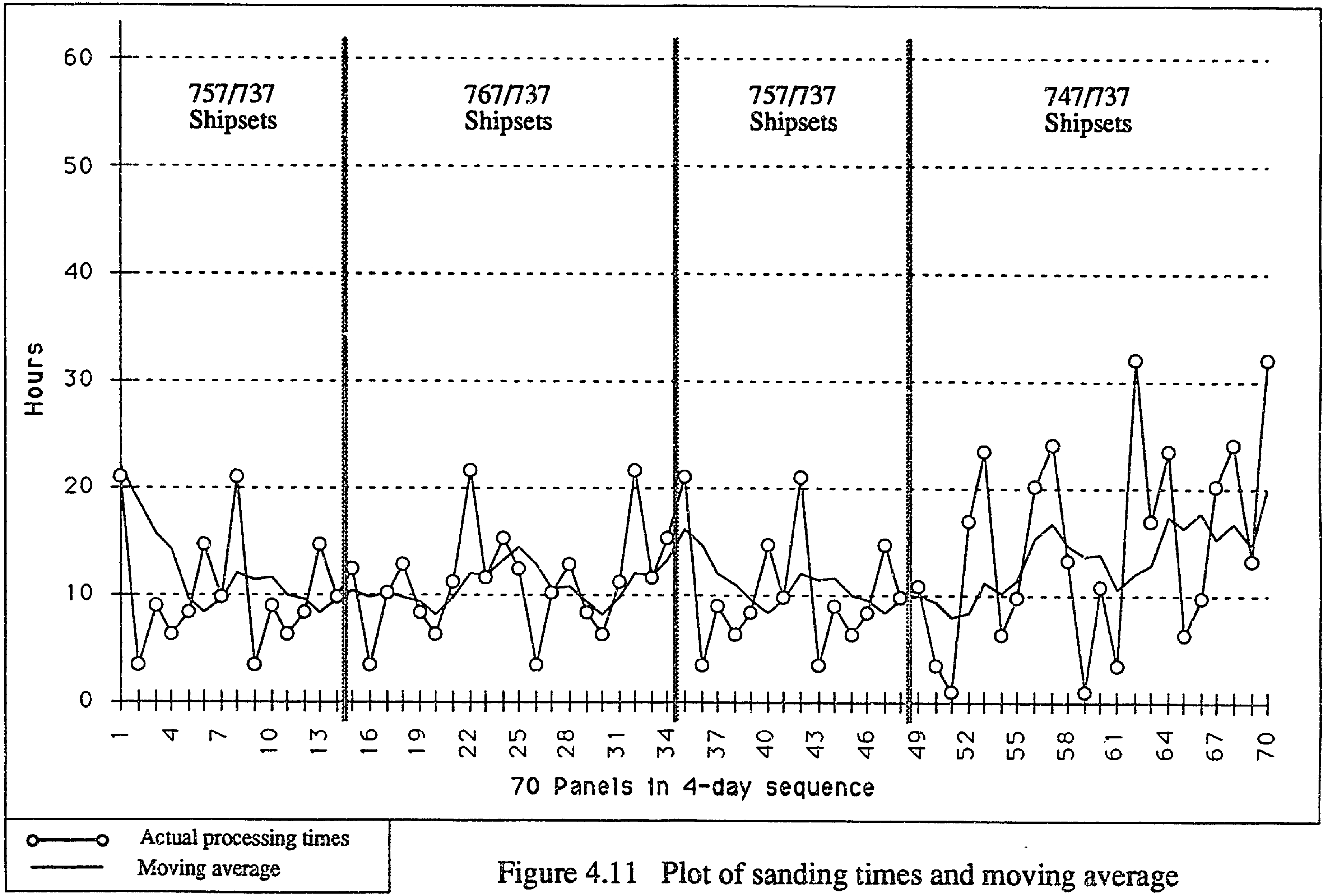


Figure 4.11 Plot of sanding times and moving average

Sanding generally takes less time than hand work, and it varies less in magnitude. The sanding moving average displays similar trends to hand work, in that it is generally higher for 767 and 747 sets than for 757. Sanding is plotted with the same vertical scale range as hand work to better visualize the difference in levelness.

Despite the relative roughness of the moving averages, the complexity of panels is rather well distributed. If it were not for the approximate correlation between the hand work and sanding times, the moving average would likely be even rougher than it is, so the little correlation which does exist ($R^2 = 25\%$) is beneficial to leveling. See figure 4.12 for a scatter plot, regression line and residual histograms. The two outliers circled are 747 and 767 rear webs which require extensive hand work.

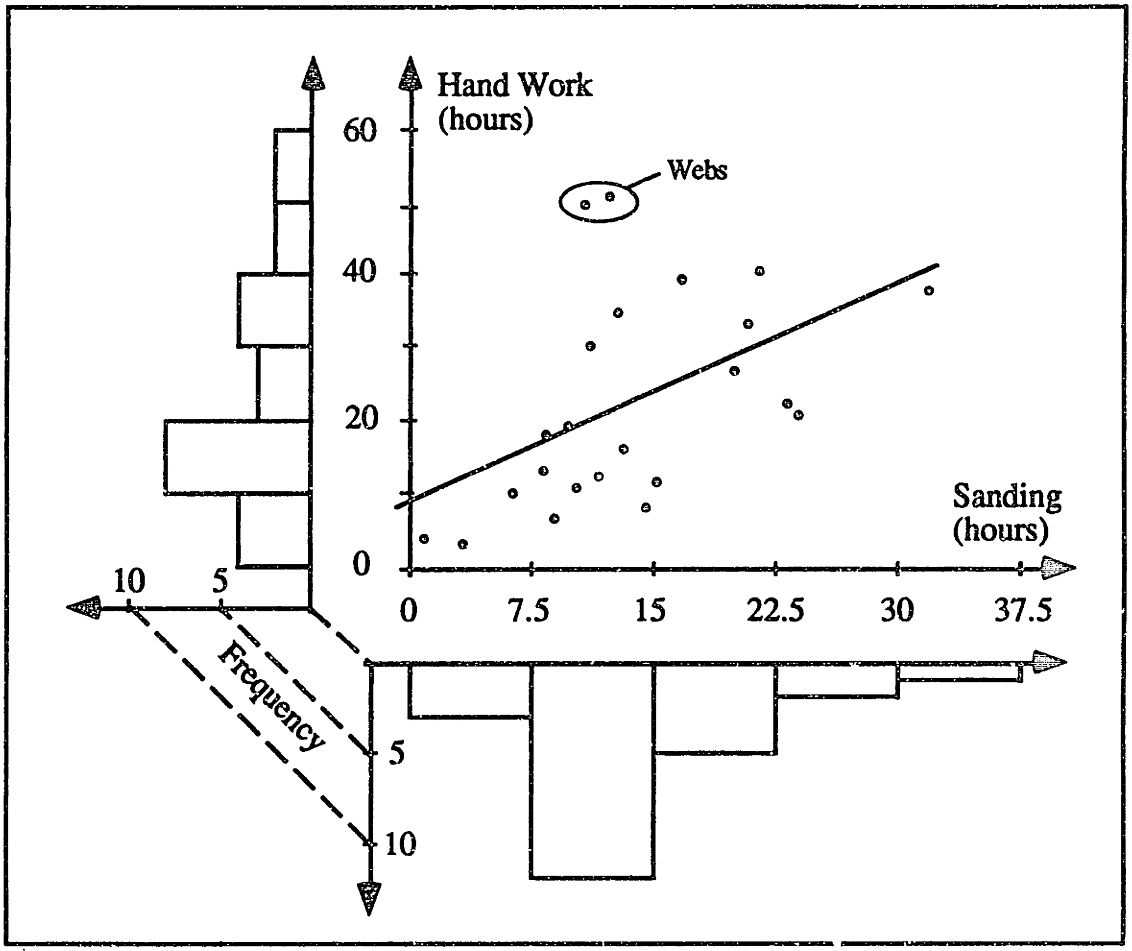


Figure 4.12 Combined scatter plot and histograms of hand work and sanding times

Impact of Variation in Moving Average

The objective of this analysis was to develop a sequence of panels that would allow the shop to run synchronized as an assembly line, with all panels advancing together every takt time, needing no buffer WIP. The moving average trends just presented impose a complication. Since the moving average value at any time represents the total amount of work in the station, when the average is high, the work content is high, requiring extra workers to keep parts flowing; and when the average is low, the work content is low, resulting in fewer workers needed. Unfortunately, this is opposed to leveling which seeks constant resource utilization rates.

Since these drifts in the moving average resulted from shipset sequencing, one way to maintain a leveled number of workers is to develop a sequence with all shipsets mixed together, further smoothing the demand on resources, but that would mean abandoning the shipset sequence concept. This thesis doesn't address such a full-mix leveled schedule, though one could be developed using a method similar to the one presented here. The results of such an analysis would likely show smoother manpower needs, reduced WIP, increased FGI, and more difficult planning and tracking as compared to the shipset analysis described here. A full-mix leveled schedule would be a good follow-up study. The remainder of this analysis continues with shipset processing.

Regarding Synchronicity

Again, trends in the moving averages negatively impact this proposal, especially in the area of WIP requirements. To keep the amount of resources and the demand on these resources level, the strict synchronization will have to be abandoned, although the 1.275 hour takt time is still a useful quantity for analytical purposes.

Earlier, the four 737-7X7 groups were referred to as "days," as if each group would pass through any given sub-process in exactly one day. Actually, the four groups don't each fit into a single 21.51 hour production day. The 737-757 group takes less, the others more, as one would expect due to the greater complexity of the 767 and 747 over the 757. However, the four groups together do fit into four days, by definition. Dividing the 70 panel sequence into four days' production can be done two ways: (1) same number of panels each day, or (2) same total processing hours each day. The first option gives 70 panels / 4 days = 17.5 panels per day. Unfortunately, this type of division is made useless by the variation in processing time moving average, for groups of 17 or 18 consecutive panels will have different total processing times, requiring slack resources. The second option is more useful: divide the sequence into four groups with each getting approximately one quarter of the total processing time.

Hand work for all 70 panels requires 1408 hours, or 352 hours for each of the four days. The following chart (Fig. 4.13) shows where the 352-hour divisions fall within the 70 panel sequence. Sanding divisions are also shown. Note that these groupings are not the only possible ones; by redefining which panel in the 70-panel sequence is number 1, different groupings would result, and the number of panels in a given day would vary as well. As a result, the 8 panel difference between days 1 and 4 in sanding could come out a bit larger.

The different numbers of panels in a given day have two implications:

1. Each process will run a different number of panels on each of the four days
2. The difference between largest and smallest daily production will require additional idle buffer WIP. For example, after sanding there will be a buildup of a few extra panels on day 1 which remain until sanding slows down on day 4. This point is addressed further in the following section.

	Total Hours	Hours/ Day	Day 1 Panels	Day 2 Panels	Day 3 Panels	Day 4 Panels
Hand work	1408	352	1 to 21* 21 panels	22 to 38 17 panels	39 to 56 18 panels	57 to 70 14 panels
Sanding	836	209	1 to 21 21 panels	22 to 39 18 panels	40 to 57 18 panels	58 to 70 13 panels

*Key: 1-21 means panels #1 through #21 in the sequence are run on that day.

Figure 4.13 Division of shipset sequence into four production days

INVENTORY LEVEL REQUIREMENTS

Having developed a new scheduling method for the plant, one which should allow better synchronization and WIP reduction, the next question is, "How much WIP will this system need?" TPS endeavors to eliminate all buffers, all slack, all safety stock. Even Toyota hasn't achieved this goal, but they are getting closer all the time. Based on the leveled schedule presented above, the minimum WIP required to sustain this system is derived next. The goal is to drive out all the slack, but some has been left in to compensate for parts of the process which couldn't be quantified. For some areas, physical plant changes are proposed to facilitate the WIP reduction.

Method for Calculating Minimum WIP

Once the process variation is sufficiently reduced, the average number of in-process panels can be determined for each process. To do so, first calculate the total monthly processing time needs for each process, then divide it by the monthly number of panels

(350) to find the average processing time. Then use that average time to find the average number of in-process panels needed:

$$\text{Number of panels} = \frac{\text{average processing time}}{\text{takt time}}$$

For some operations the required number of panels can be reduced through parallel processing. For example, since workers can double up on hand work and sanding, the number of panels in these processes could be cut in half. Based on this, what has been called "average panels in process" might be better called "average required parallel processors." The purpose of takt time is not to have the same number of labor or processing hours on each part, but, rather, the same number of clock hours in the process. For example, a difficult panel might have three people working on it, while a simple panel might have only one person working on it; but both panels would be in-station for the same integral multiple of the takt time.

Even in the leanest production system, there is still some idle WIP needed. Several factors increase the required amount of idle WIP between stations in the shop:

1. Transportation time between processes, which varies depending on the type of transportation

2. Hourly fluctuations of the workload currently in the process, a result of imperfect leveling

3. Variations in manual processing times for a given panel, resulting from different workers, rework, repair, etc.

4. Variation in machine processing time due to equipment problems

5. Disruptions resulting from special or emergency panels: AOG[37], 707/727 spares requirements, and custom panels

6. Worker variation: turnover, seasonal absenteeism

As this analysis is meant to be only a first-cut approximation, the following calculations of WIP levels considers the impact of only the first two factors: transportation, and workload variation. The third one, manual process variation, is omitted because (1) it can be reduced through diligent analysis and experimentation, and (2) this model presumes such variation reduction has been done. Machine variation is currently a significant hindrance to smooth flow through the plant---since reliable and available equipment is a pre-requisite to my proposal, it too was omitted.

The fifth factor cited above is also omitted, though it is the hardest to control. The plant has certain obligations to supply service parts and to run experimental or special order parts, all of which disrupt the leveled sequence and often place extreme demands on resources. Trial runs on the mill and peening machines for instance are extremely disruptive. It is omitted because quantification was difficult.

The following calculations assume a constant level of resources at each process. This, combined with imperfect leveling, causes WIP levels to fluctuate a bit. One way to reduce WIP fluctuation and to keep the plant more synchronized, is to vary the resources at each process in response to changes in demand. This would mean working overtime on heavy days, or moving workers between processes as demand varies. In forming, for example, the peening machines would be underutilized during a 737-747 shipset, so these workers could be used elsewhere, such as doing manual peening in the hand work area.

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[37] AOG means Airplane On Ground, in reference to a previously sold airplane which has been grounded due to damage and quickly needs a part so it can be returned to service.

Or if sanding had a high work load at the same time that hand work had a light work load, some of the hand workers could assist in sanding. This work force flexibility is a desirable TPS improvement, but is omitted in the analysis.

Minimum Inventory Calculations

This section presents process-specific calculations on required WIP. Data for these calculations are summarized in figure 4.14. For each process, the WIP calculation is as follows: (1) processing time determines the required number of in-process panels; (2) variation in levelness determines the required buffer; and (3) transportation time requires additional buffer.

Milling

Setup and run time both depend on part size, complexity, and number of panels on the machine bed. As discussed in the previous chapter, the lot size goal is one bed full. When this is achieved, the average number of panels on a bed will be 3.3. The calculation is shown below. The numerator 70 is the number of panels required in a week, and is divided by the number of machine beds full run in a week. The denominator multipliers of 2 are to double the number of beds, since both left and right hand lots must be run. The symbols '#X' refer to the number of different panels for which a bed full is X panels (If there are 12 different panels for which the bed holds 2 panels, then #2 = 12.) The other multipliers of 0.5 and 0.25 are to reduce the number of machine beds run in a week, since, for example, a 4-panel bed need be run only once in four weeks.

$$\frac{70}{2(\#1)+2(.5)(\#2)+2(.25)(\#4)}=\frac{70}{2(2)+2(.5)(12)+2(.25)(10)}=\frac{70}{21}=3.3\,panels\,/\,bed$$

Since there are eleven machines, there would be about ten machines cutting at any time (the other in setup), so ten beds of parts would be full of panels, which gives on average

$$10 \text{ beds} * 3.3 \text{ panels/bed} = 33 \text{ panels in process}$$

More significant than the in-process panels is the idle WIP after milling. As described in Chapter 3, the TPS plan has the mills machine in small lots, store the panels in a buffer, and then the sanders pull panels from the buffer in a predetermined sequence. Since the lot size is one bed full, there will be, on average, one-half bed full of each type of panel in the buffer.

$$\text{Buffer size} = 0.5 * \sum \text{number of panels in all beds full} = 69 \text{ panels}$$

Since panels leaving the mill are placed into the WIP buffer, transportation is decoupled from the sanders, so no additional WIP is needed to cover for the transportation time. The total milling inventory, then, is 33 on mills + 69 buffer = 102 panels.

Panel	Bed full	Hand Work hours	Sand hours
767 rear spar web	2	51.3	12.3
767 frt spar web	2	30.5	11.2
767 #1 upr pnl	2	12.1	15.3
767 #2 upr pnl	4	11.0	10.2
767 #4 lwr skin	4	12.6	11.6
767 #1 lwr skin	4	13.2	8.2
767 #2 lwr -enc pnl	1	41.3	21.5
767 #3 lwr skin	4	35.5	12.8
Total one side	26	207.5	103.1
757 #1 upr	2	8.3	14.6
757 #2 upr	4	6.6	8.9
757 #1 lwr	4	18.4	8.4
757 #2 lwr-enc pnl	4	34.0	21.0
757 #3 lwr	4	19.8	9.8
Total one side	18	87.1	62.7
747 rear spar web	2	50.4	10.8
747 frt spar web	2	47.7	9.8
747 OB frt spar web	2	3.9	1.0
747 #1 upr	1	21.2	24.1
747 #2 upr	2	22.6	23.4
747 #1 lwr	2	16.6	13.2
747 #2 lwr-enc pnl	2	38.2	32.0
747 #3 lwr	2	27.5	20.1
747 mid spar web	2	40.1	16.8
Total one side	17	268.2	151.2
737-300 #2 upr	8 sp	3.3	3.3
737-300 #1 upr	8	10.2	6.3
Total one side	8	13.5	9.6

Average panels/bed	3.3	4-day cycle total	1407.6	hours	836.2	hours
		Average	20.1	hours	11.9	hours
		Takts	15.8		9.4	
		Workers	16		10	
		Work Stations	7		5	

Figure 4.14 Information for WIP calculations

Sanding

Sanding time varies significantly among the panels, from 1 to 32 hours (Fig. 4.14). Since the average panel requires 11.95 hours, the average part requires 11.95/1.275 hours = 9.37 takt times of work. Sanding, then, requires ten workers. Since sanders can (and currently do) double or triple up on a panel, fewer than ten in-process panels will be needed. Assume five work stations, requiring workers to double up. An average panel will then be in the process for 5 * 1.275 = 6.375 hours.

As discussed earlier, the variation in the moving average of demand (Fig. 4.11) results in a different number of panels being processed each day. For sanding the number varied from a high of 21 to a low of 13 panels per day (Fig. 4.13). This 8-panel difference requires a WIP buffer to absorb the variation. So after sanding, assume a buffer which varies from zero to eight panels, and averages four.

In addition to this buffer is the need for transportation to forming. When the post-sanding buffer is empty, panels will go from the sanding table straight to forming. To cover this handling time, one panel of idle WIP is added, providing over an hour of available handling time. The total WIP, then, is 5 panels being sanded + 4 panels average buffer + 1 panel transportation buffer = 10 panels.

Forming

A panel's demand on forming resources depends on several factors:

- Process complexity: whether chip formed, which peening machines are needed
- Panel size and complexity: for masking and peening time
- Amount of handling time: loading, movement on overhead rail and shuttle, unloading
- Contour inspection time

Since detailed panel-specific information was unavailable for these processes, the approximate times are informed estimates. Also, since this part of the process is so complex, it is likely that the analysis is least accurate here.

1. Chip-form: Allow one takt time
2. Load on rail: It takes an hour or two to load and mask the skin for peening, so allow two takt times
3. Span-wise peen and machine sand: Run part in one takt, move to sanding machine in a second, sand in a third, transport to chord-wise peen in a fourth
4. Chord-wise peen: Run in one takt, transport to next step in a second
5. Inspect 747 contour: Lower and check with templates in one takt time, move to compression peen in a second
6. Compression peen: Run in one takt time, move to inspection in a second
7. Inspect peening properties: One takt time
8. Unload: One takt time
9. Inspect contour: One takt to load onto fixture, one to inspect, one to unload and transport to the hand work area

A sum of the above steps gives 18 takt times, or 22.95 hours, just over one day. Again, of the whole plant WIP estimate, this portion is likely to be most inaccurate, however, the error is likely on the conservative side, since each transportation has been allowed one full takt time.

The 747 and 767 shipsets are likely to be more challenging to run than the 757 sets, which introduces buffer requirement after forming to absorb the variation in the level schedule. The amount of buffer needed to absorb the variation is impossible to determine with the available data, so a value is assigned proportionally similar to that needed after sanding and hand work. For both of those operations, the levelness variation requires buffers that are 50% to 80% as large as the number of in-process panels. Since forming is machine-paced, 10 panels are allowed for the buffer, which is the lower end of that range.

Moving panels from the checking fixtures to the hand work process takes negligible time, so no additional panels are needed to cover for transportation time. The total WIP for forming, then, is 18 in process + 10 buffer = 28 panels.

Hand Work

This calculation is nearly identical to that for sanding. An average panel requires 20.11 hours, or 20.11/1.275 = 15.77 takt times, which requires 16 workers (Fig. 4.14). Doubling and tripling workers on panels allows 7 panels in-process, resulting in 7 * 1.275 = 8.925 hours in process. The variation in workload moving average (Fig. 4.10) results in daily output that varies from 14 to 21 panels (Fig. 4.13). The 7-panel variation results in an average buffer of 3.5 panels. After hand work, the mylar template inspection takes a few hours. The webs are transported across the plant to the layout tables for a flatness check. Add to this one panel of buffer to cover for transportation to the tank line, and the total hand work WIP is 7 in-process + 1 transport to layout tables + 3 inspection + 4 buffer + 1 transportation to tank line = 16 panels.

Tank Line

The processing time from load to unload is about two hours. Since this is greater than the takt time, two panels are needed in process. The carrier can hold two panels or more, so tank line congestion can be reduced by always running at least two panels on a carrier. Since the two panels must be in the same alloy group, this may require an additional buffer panel for loading. Thus the buffer before the tank should be three panels to guarantee a choice of two from the same alloy group. After the tank line, panels are inspected and touched up, adding another rail full of panels, typically two panels. The transportation time from the tank line to paint is negligible. Total WIP, then, is 3 loading buffer + 2 in process + 2 inspection = 7 panels.

Painting

The painting process is very smooth, except for the occasional enclosure panel, for which the fuel access panel openings must be prepared. If this were begun during inspection after the tank line, and assuming an additional takt time were taken to complete the preparation work, one panel is added to WIP for this preparation time. The actual painting process is rather simple, and the booth holds two or more panels at a time. Allowing two takt times for painting, results in two panels WIP in the booth.

After being painted, the panels are moved out of the booth and into an oven for a one-hour bake. After baking, another takt time is needed for cool-down before the finishing operation. The total WIP, then, is 1 prep + 2 paint + 1 in oven + 1 cool down = 5 panels.

Finishing

Cutting off the handling tabs and treating the exposed surface should take no more than two takt times. Add another takt for the chemicals to dry before handling. Transportation takes an insignificant amount of time, so total WIP is three panels.

Raw Material and P6

With the mill lot sizes reduced to one bed full, only about a week's worth of raw material is needed on-site. However, considering the significant transportation time from Alcoa and the importance of not starving the mills, one month's worth of inventory (350 panels) may be more reasonable. As was argued in Chapter 2, Boeing should improve internal operations before pressuring suppliers for significant changes. The shop should work with Alcoa to determine if Alcoa's plant can produce smaller lots of raw panels. If they can't, then reducing RM inventory on-site will just shift inventory from Boeing's building to Alcoa's.

The level of finished panels in P6 can eventually be reduced to a fixed number of complete shipsets. Shipset processing allows the P6 inventory to be leveled, eliminating the current imbalances shown in figure 4.2, where there are eight of some 767 panels but only four of others. The level of P6 inventory probably should be lowered last, after the shop has proven its reliability with the TPS process. Eventually, it should be possible to operate with at most four day's inventory, one complete 4-day cycle, which is 70 panels.

COMPARISON OF TPS AND CURRENT PERFORMANCE

This section compares quantitative measures of Boeing's current operations with the results obtained in the preceding analysis. Figure 4.15 is a summary comparison of inventory levels and resultant flow times. The current flow times are based on the shop's current actual production rate of 300 panels/month, while the TPS flow time is based on the analysis' production rate of 350 panels/month, which slightly exaggerates the flow time improvement. The WIP level improvement, however, is a realistic and undistorted 63% reduction. The amount of post-mill WIP (that is WIP from sand through finish) which is being pulled through the shop is reduced from 444 panels to 69 panels, an 84% reduction. Notice that the WIP in mills is actually increased by the new TPS system, which is due to the buffer between the mills and the sanders, from which sanders pull panels in sequence.

	RM	Mill	Sand	Form	H/W	Tank	Paint	Finish	P6	Total
Current inventory	767 panels	80	78	147	82	68	69	300		1591 panels
TPS inventory	350 panels	102	10	28	16	7	5	3	70	591 panels
Current flow time	54 days	5.6	5.5	10	5.7	4.8	4.8	21		111 days
TPS flow time	21 days	6.1	0.6	1.7	1	0.4	0.3	0.2	4.2	35 days

Figure 4.15 Inventory summary comparison

An additional benefit of shipset processing is more consistent flow time. Currently, flow time can vary widely for a given panel. Figure 4.16 illustrates the current level of flow time variation. The flow times given are actual data for 767 panels processed through the shop during the fall of 1991. The columns represent eight data points for each type of panel, four left hand and four right. The numbers are flow time in "manufacturing days," which excludes weekends and holidays. The data points 1 through 4 for a given hand and panel were all released into the shop within a few days of one another, yet their completion dates vary significantly, as shown by their respective flow times. Notice that the times generally increase from L/R1 to L/R4, likely due to the priority scheduling, since the first panel in the batch is closer to its due date, whereas the fourth panel has more time to spare. The ones due sooner get higher priority from the scheduling computer, so are likely pushed through quickly, while the lower priority panels are allowed to sit in WIP.

767 Panel type	**L1**	**L2**	**L3**	**L4**	**R1**	**R2**	**R3**	**R4**
Rear web	20	30	30	60	11	12	63	31
Front web	12	20	35	23	18	19	21	27
Upper #1	20	38	24	42	17	21	28	31
Upper #2	34	26	16	21	11	15	23	14
Lower #1	13	17	40	22	16	19	31	44
Lower #2	12	17	45	19	12	22	23	31
Lower #3	19	53	18	36	12	19	28	56
Lower #4	14	16	9	40	21	14	23	27

Figure 4.16 Actual flow time for 767 panels (in days)

With the fixed sequence proposed in this thesis, every panel has the same flow time, because they all move through the shop at the same rate, paced by the takt time. This eliminates the flow time variation shown above.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This chapter is a reiteration and summary of conclusions and recommendations presented in Chapters 2, 3, and 4. First are presented ideas on the general, company-wide applicability of TPS. The second group is ideas on specific types of shops. Finally, the skin and spar shop is summarized.

GENERAL APPLICABILITY

Because of differences between the two companies, most TPS implementations at Boeing will be of a different form than at Toyota. Thus, Boeing's unique business requires thoughtful implementation of TPS, not merely copying the techniques.

All of the TPS concepts are applicable to Boeing's operations, but some concepts are more applicable than others, for an individual shop and for the company as a whole. There is also a difference in the implementation time frame.

For most TPS concepts, the degree of applicability varies between plants. For some TPS concepts, such as quick setup and standard work, applicability is clearly differentiated between assembly and fabrication operations. Thus, different plants will require different implementation plans.

JIT This is one of the most difficult practices to apply in Boeing, for two reasons (1) tremendous product complexity, and (2) widely dispersed supplier network. It is highly doubtful that JIT at Boeing could ever be as finely tuned as at Toyota. Also, Boeing should develop an internal expertise and commitment to JIT before coercing its supplier network to adopt the technique.

Kanban Kanban may not be very helpful for interfacing Boeing's assembly plants to suppliers or fabrication shops. Toyota's kanban usually triggers actual manufacture of the parts, which may be unreasonable for Boeing, given the complexity and lead time of many airplane components. If kanban were used for complex parts, it could only trigger shipment, not manufacture. However, there are many simple parts such as hydraulic tubes or subassemblies which can be produced with short lead times and which could be ordered via kanban.

Kanban is most appropriate at Boeing for four situations:

1. Controlling the production flow inside individual fabrication or assembly operations
2. Triggering manufacture of simple components at local suppliers
3. Purchasing off-the-shelf components and supplies from local suppliers
4. Signaling delivery of complex parts which were ordered ahead of time by the computer scheduling system

Lot size/Setup time Smaller production lots would reduce inventory, saving Boeing significant amounts of money in inventory carrying costs and reduced obsolescence. Reducing lot size will be difficult to attain without other significant changes such as setup reduction and improved shop flow control. Therefore, Boeing should pursue quick setup as a way to reduce idle time and flow time first, before reducing lot size.

Standard Work

Assembly plants Boeing already uses standard operations (detailed job instruction sheets) due to strict safety requirements. Most Boeing assembly plant tasks are too variable or too complex for the level of detailed planning that Toyota puts into its standard work. However, some assembly operations are repetitive and could be more tightly controlled (such as installation of the passenger windows)---this repetitive process could be studied and standardized. Boeing's operations could also benefit from standardizing and improving common procedures such as housekeeping, handling parts and getting blueprints. Standard timing is not applicable in the way Toyota uses it, due to job complexity and learning curve. Standard WIP isn't an issue in assembly, either---since the line is rigidly paced, processes are not able to work ahead of schedule.

Fabrication plants There is considerable applicability of standardized work in the fabrication plants. In all shops, it could be used to remind and inform operators about general job duties such as housekeeping, inventory control, etc. In some fabrication plants, workers have no repetition---their jobs are always new, they're always doing something different, running hundreds of different parts. They have no regular cycles, no regular sequence of operations. Thus, creating step-by-step instructions would be impractically time-consuming or even impossible. However, as in the assembly plant, standardized procedures would be useful for common tasks, for repetitive or frequently-performed operations.

Inspection Because of the complexity of large airplanes and the overriding concern for safety, final inspection will likely never be eliminated---but Boeing can certainly gain a great deal by eliminating intermediate and incoming inspection steps. Reducing in-process inspection will require improvements in the reliability and accuracy of manufacturing processes and vendors.

The current role of the Quality Assurance department will be significantly changed and its size reduced. Former inspectors should assume a new role of training workers in SPC and other techniques, to be quality teachers and coaches, rather than overseers.

SHOP-SPECIFIC APPLICABILITY

Each Boeing plant has unique characteristics which suggest differing degrees of TPS applicability and differing approaches to implementation.

TPS is more applicable to Boeing's fabrication operations than to final assembly, and fabrication operations have the greatest potential for improvement in the near term. Among the fabrication shops, TPS is more applicable to flow shops than to job shops.

For fabrication shops, the general benefits of TPS are improved process reliability and responsiveness, leading to reduced inventory and flow time, which in turn reduce lead time and cost. Job-shop fabricators should use an improvement strategy that begins with reducing setup time and lot size, then simplifying operations by organizing the shop into cells, each of which manufactures a group of similar components. Flow fabricators should use an improvement strategy that begins with reducing setup time and lot size, then straightens the flow, then levels the production schedule, more tightly links the processes, and works down the inventory, resulting in reduced flow time.

Self-contained fabrication shops (ones which control the stock every step from raw material to finished goods) such as the tube shop may be where learning should occur first, because such shops have the freedom to experiment with material flow and scheduling more than other shops.

Assembly plants, due to their risk aversion, would likely find it more difficult to experiment with JIT than would the fabrication shops.

SKIN AND SPAR SHOP APPLICABILITY

The basic conclusions of the skin and spar shop study are as follows:

- TPS has significant applicability in this shop
- Skin panel fabrication should be thought of as a flow process rather than a job shop
- TPS has the potential to significantly reduce inventory and flow time in this shop

In general, most of the TPS practices are applicable for this shop. Because the panels are a standardized product and are produced in uniform volumes, they are excellent candidates for level scheduling, pull, standardized operations, and other TPS practices.

TPS inspires a fundamental shift in thinking for this shop, from a job-shop mindset to a flow-shop mindset. The vision is a level-scheduled, mixed-model processing line, synchronized by pull signals. The plant should think of its process as an assembly line. This assembly line approach begins with a leveled work schedule, with panels sequenced to reduce the variation on demand for resources. The panels would remain in this same sequence throughout the process. Movement between operations would be based on kanban pull signals to control inventory levels. Work-in-progress would be reduced and pushed upstream to a single stock after the mills. Further development has the plant sequencing the panels so that all the panels comprising a matched shipset are completed on the same day.

Achieving this level of performance will require management commitment, a few years of hard work, and changes in the plant's culture and facilities. Support staffs must assume new roles. Machine maintenance must be improved. The mills must reduce their lot sizes, requiring quicker setup. Internal transportation must be improved to provide smooth, short, quick flow. Processes need to be standardized to reduce variation.

The specific conclusions and recommendations for each process are summarized below:

RM Reduction should not be an early focus for improvement efforts. First the shop should improve its internal operations.

Milling The critical applications of TPS to the milling operation are quick setup and smaller lots. Since the mills can't respond quickly to a pull signal from the sanders, there should be a WIP buffer from which sanders pull milled panels according to their schedule.

Forming The quickest route to improving the forming bottleneck seems to be reducing the constant shuttling of panels along the overhead rail system.

P6 As the skin and spar shop becomes more predictable and reliable, the P6 inventory level can be reduced. Whatever safety stock P6 decides to keep on hand, it should be in integral shipsets. P6's role then becomes one of managing vendor parts and providing a small safety stock.

Control Simple systems and visual control can be used for planning production and for tracking inventory through the shop. Shop management must agree to reduce emphasis on traditional monitoring-oriented metrics and focus more on improvement-oriented metrics.

Analysis The analysis presented in Chapter 4 demonstrates how the shop's level schedule can be developed. The result is an inventory reduction from 1600 to 600 panels, and flow time reduction from 40 days through the shop down to ten days.

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