

**REDUCING FLOW TIME IN AIRCRAFT MANUFACTURING**

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## REDUCING FLOW TIME IN AIRCRAFT MANUFACTURING

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The assembly of aircraft is a labor-intensive process that exhibits a significant learning-curve effect and that requires long flow times and costly work-in-process inventories. This paper presents research that describes the production context, quantifies the cost of flow time in this context, identifies the causes for the long flow times, and shows how improvements in labor productivity can be used to reduce flow times. Boeing is implementing the recommendations from this research and has obtained significant benefits from reducing flow times.

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## INTRODUCTION

The cost accounting system at Boeing does not consider flow time, the time required by the production system to manufacture a product, as a significant manufacturing cost. Current emphasis on schedule adherence, along with close management attention to head count, encourage production supervisors and planners to maintain flow time and minimize head count. In this research, we show that flow time is a significant manufacturing cost and that exclusion of this cost has resulted in production decisions that over emphasize head count reduction at the expense of flow time.

In this paper we report the results from a thesis internship performed by the first co-author at The Boeing Company, the world's most successful airplane manufacturer. The internship was conducted as part of MIT's Leaders for Manufacturing Program, and ran from June 1990 through December 1990 in the New Airplane Division (now known as the Boeing 777 Division). The charge for the internship was to study the Boeing 7A7 final assembly process at Boeing's Washington facility to discover lessons from 7A7 manufacturing and to make specific recommendations for the 777 program.

After learning about aircraft manufacturing the project quickly focused on manufacturing flow time, and the questions of what does it cost, why is it so long, and what needs to happen to affect it. Doing things fast is a common theme in the best manufacturing practices and is advocated at length in the current manufacturing literature, e. g., Dertouzos et al. (1989), Goldratt and Fox (1986), Hayes et al. (1988), Schmenner (1988). This research examines how these ideas apply to aircraft manufacturing and provides a case study for addressing flow time issues.

We believe this study is a good example of action-oriented research which considers real operations with real problems, and attempts to develop, extend and apply new concepts. From this research, we can extract manufacturing principles that may be of generic value to other manufacturing contexts. Finally, this research can lead to significant, measurable impact for the company under study. In all modesty, we hope this can be one example of a new direction for operations management research.

In this study, the main lessons from the research are (i) the importance of recognizing and quantifying the cost of flow time in aircraft manufacturing; (ii) the consideration of reducing flow times, rather than head count, to realize the productivity improvements from the learning curve; (iii) the differences in impact from how flow time reductions are enacted, i. e., whether a reduction is pushed back or pushed through the production process; and (iv) the value from a data-driven examination of the impact of system variances on labor content and flow time.

The rest of the paper is organized into four sections. We first describe the organization and planning for the manufacture of an aircraft. Next we discuss the costs of flow time and show how to quantify these costs; we propose a strategy for flow time reduction based on productivity improvements from learning. We then present regression analyses that demonstrate the impact of system variances on direct labor content and discuss the implications for a longer-term strategy for flow time reduction. We conclude with the impact on Boeing from this work.

# PLANNING OF AIRCRAFT MANUFACTURING

## Introduction

In this section, we describe some of the key concepts in the planning of airplane manufacturing. Specifically, we describe the organization of the manufacturing processes for airplane assembly and the methods for planning and scheduling the assembly operations. At a company like Boeing, planning is an enormously complex activity and involves hundreds of people with thousands of person-years of experience. Needless to say, we will at best give a high-level overview of the methodology, concepts and planning tools.

## Description

The assembly of an airplane entails a synchronized series of manufacturing processes which are organized as a network of concurrent and merging flows. These manufacturing processes are comprised of operational work units or departments called control codes. These control codes, staffed with varying numbers of line employees, have responsibility to perform pre-assigned tasks within the manufacturing process. The operations performed by these control codes vary from tasks as simple as finishing the surface of an airplane wing to tasks as complex as integrating the major body sections of the entire airplane. For example, a control code might be responsible for joining the completed left and right wings to the wing stub section of the airplane fuselage (wing-stub join).

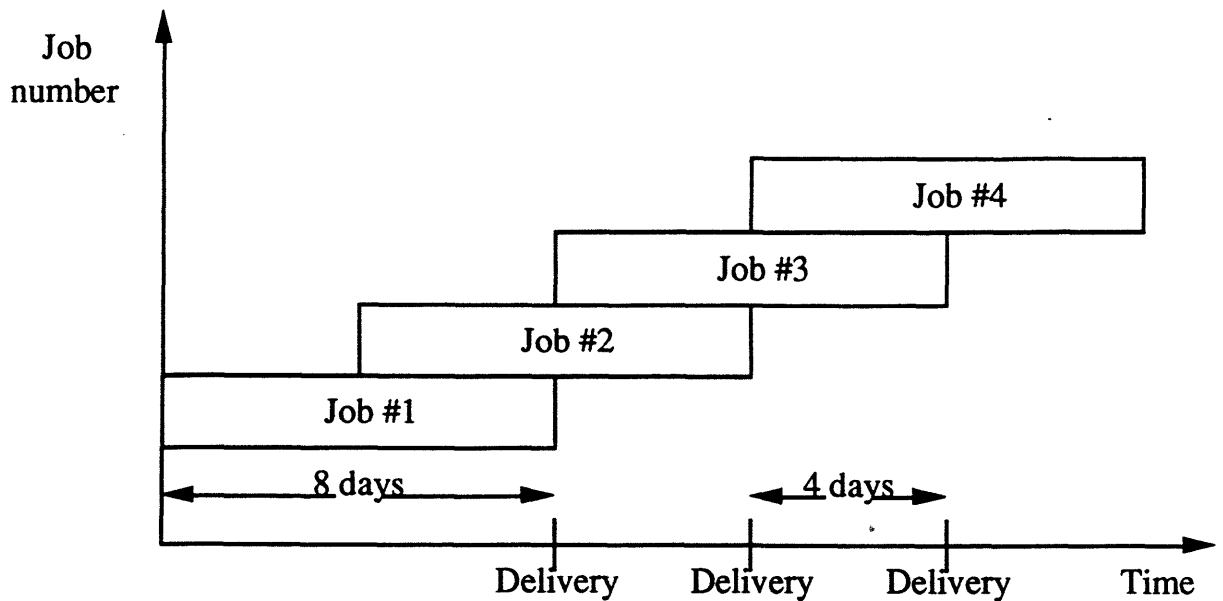
The *manufacturing flow time* for a control code is the elapsed time (in work days) planned for a control code to perform and complete its required tasks; in some industries, this flow time is also known as lead time or cycle time. The control-code flow time is the length of time that an airplane will remain in a specific control code before moving to the next control code. Different control codes within the manufacturing sequence can have (and will have) different flow times.

The *production cycle time* (or rate) is the elapsed time (in work days) between consecutive job completions for a control code or between airplane deliveries for the entire manufacturing system. Unlike manufacturing flow

time, all control codes within the manufacturing system must operate at the same production cycle time. An airplane manufacturer operating at a three-day production cycle completes and ships an airplane from the production line every three days. Consequently, every control code must also complete work on an airplane every three days, no matter what the individual flow time of the control code is. Correspondingly, every three days, one new job enters each control code in the manufacturing process.

To illustrate the concepts of flow time and cycle time, consider a control code which has eight days of flow time and operates on a four day production cycle; the flow time is often a multiple of the cycle time, although this is not mandated. The control code has eight days to complete its required tasks on each plane and ships a completed job to the next control code every four days.

The number of job or tool positions required within a control code is simply the quotient of the control code flow time divided by the production cycle time, rounded up to the next largest integer. So, a control code with eight-day flow times and a four-day production cycle has two job or tool positions. The schedule for such a control code is shown in Figure 1. Similarly, a control code with eight days of flow time operating on a three-day production cycle requires three job or tool positions. The schedule has a plane entering the control code at three-day intervals and a plane exiting the control code at three-day intervals; however, unlike the example in Figure 1, the arrivals and exits do not occur on the same day. As a result the number of job positions occupied by planes will vary between three and two over the three day cycle.



**Figure 1: Illustration of Flow Time versus Production Cycle Time**

The material handling for aircraft assembly is a substantial undertaking that requires both special equipment and extensive planning. A new job arrives at each control code exactly one production cycle after the last arrival. Similarly a job departs from each control code exactly one production cycle after the last departure. The scheduling of the material handling system is driven by these requirements. Since aircraft work-in-process and subassemblies are quite large, large overhead cranes perform many of the moves in the factory. Since most control codes only work one shift per day, much of the movement between control codes occurs during the off shifts. Scheduling these cranes so that the moves occur according to the plan is a very complex task.

The *number one flow chart* depicts the exact sequence of every control code in the airplane manufacturing process (see Figure 2); there is a new number one flow chart for each new airplane program, model derivative, or new production rate. The number one flow chart specifies not only the sequence of the control codes but also the flow time and start and stop dates for each control code; in Figure 2, the length of the jobs equals the flow time for the control code.

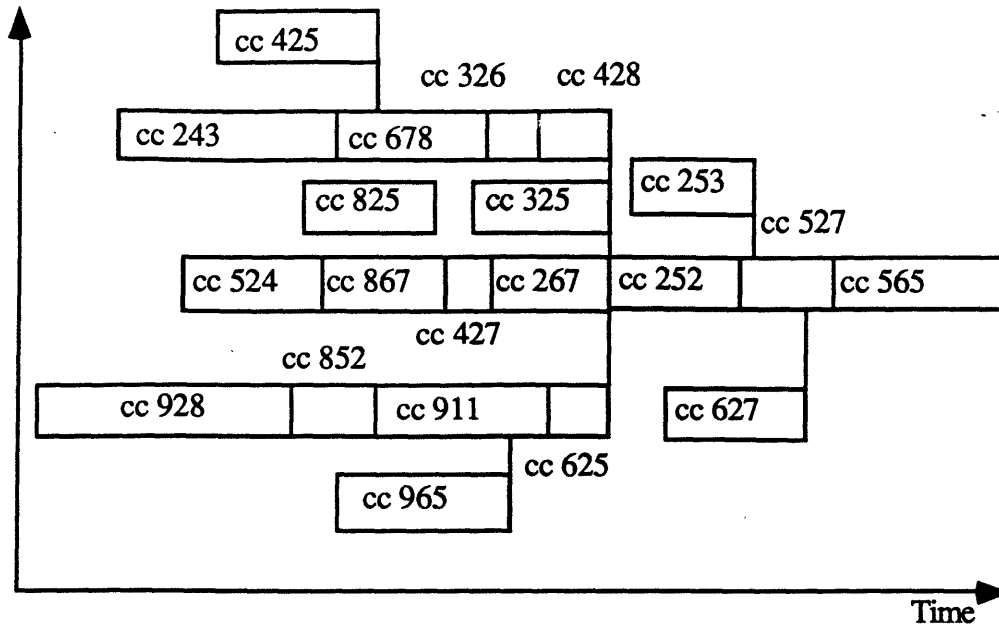


Figure 2: Sample Number One Flow Chart

The determination of the flow time for a control code depends on the manufacturing work statement and the crew size for the control code. The *manufacturing work statement* details the necessary work to be performed for a specific job in a control code. These work statements outline the exact tasks and the sequences that these tasks must be performed in. At Boeing, the Industrial Engineering department estimates the direct labor input required to complete the tasks in the manufacturing work statements. They also estimate the learning curve for a work statement, which prescribes how the work content should decrease with experience.

The *crew size* of a control code is in turn determined by crew size studies conducted for each control code. The studies determine the minimum, maximum and optimal crew sizes based on detailed examination and planning of the work content in a control code. The optimal crew size is the number of workers at the control code that minimizes the direct labor input per job.

### An example

Now, let us illustrate these ideas in an example. Suppose that by using the manufacturing work statement, we estimate that the number one production unit (i.e. the very first airplane) will require eight hundred labor hours to



assemble a plane at a given control code. Using present planning methodology, we set the crew size to minimize the direct labor per job; in this case, the crew-size studies determine that the optimal crew size is ten workers per job. Then, with one shift per day, we determine that the flow time for the control code is  $800 \text{ hours} / (10 \text{ workers} * 8 \text{ hours per worker-day}) = 10 \text{ days}$ .

If the production line is to operate on a five-day production rate, we calculate that the number of tool positions required at the control code is two (10 flow days/5 day cycle) positions. So, the control code will initially have twenty workers (ten workers per position) at the control code working on two jobs for ten days each. Every five days a new job will move into the control code and a completed job will leave.

If the flow time is not a multiple of the cycle time, the analysis is not so simple. For instance, suppose the cycle rate is one plane every four days. If the optimal crew size is to have ten workers per plane, then this implies a flow time of ten days for each plane (10 workers @ 8 hours per day \* 10 days = 800 labor hours). If the flow time is ten days, then there must be three positions. But half of the time there will only be two planes in the control code, and half the time there will be three. A new plane will enter the control code every four days and a completed plane will exit every four days: if new planes arrive to the control code on days 1, 5, 9, ..., then planes complete the control code on days 3, 7, 11, ... , where the plane that arrives on day  $x$  completes on day  $x+10$ . As a consequence, half the time (two out of every four days) the work force is working on two planes, while the other half of the time they have three planes to work on.

If this control code is staffed with three crews of ten workers, one per position, then each crew will be idle two out of every twelve days because job arrivals and exits are not synchronized. Thus, although the work statement calls for 800 labor hours per plane, this staffing plan with "optimal" crew sizes will incur 960 hours per plane (10 workers per position \* 3 positions \* 8 hr./day \* 4 days/plane). To avoid this inefficiency, industrial engineering will relax the assumption of a dedicated crew per position and examine alternative ways to schedule the work in the control code. Industrial engineering will try to develop detailed work plans that vary the crew size at

each position and that have workers moving from position to position in order to achieve high labor utilization. In this example, at least 25 workers are required to produce a plane every four days (25 workers @ 8 hours per day \* 4 days = 800 labor hours/4 days), which is the target for industrial engineering.

Alternatively, industrial engineering will examine flow times that are multiples of the cycle time, and thus facilitate scheduling of the work, albeit likely with non-optimal crew sizes. For instance, in this example it may be possible to have flow times of twelve days and three crews, each with nine workers. This staffing level incurs 864 labor hours for each plane.

### **Conclusion**

The process of planning and coordinating a complex production process such as in an airplane manufacturing plant requires extensive knowledge, experience, and coordination. In this section, we have outlined and described only some of the many different tools that Boeing's Industrial Engineering group uses to plan and coordinate this complex production process. In the next sections, we will quantify the cost of flow time and discuss how to incorporate these costs into the production planning methodology.

## **FLOW-TIME COST**

### **Introduction**

In this section we discuss how to evaluate flow time cost in a context such as Boeing's, where there has been limited attention to flow-time cost. There are three primary components of this cost: 1) inventory carrying cost, 2) revenue opportunity cost, and 3) variable tooling cost. We discuss how the lack of flow-time cost visibility causes the present production planning methodology to overemphasize head-count reduction at the expense of flow time; we conclude by recommending how to incorporate these costs into the methodology for production planning.

At Boeing, adherence to schedule is paramount. This is due to the significant cost penalties for delays in airplane deliveries. The sequential nature of the manufacturing process dictates that upon completion of each production cycle, each job in the production line must advance to the next control code in the manufacturing sequence. The delay of a single job within the sequential manufacturing process disrupts the work flow on the production line and postpones the delivery of every successive airplane by the length of the delay. Presently, if a job is not completed within the allotted flow time, the incomplete job is nevertheless moved on to the next control code so that all following airplanes in the production line can proceed to their next respective control codes. The late airplane will then have two separate crews working on it during the manufacturing flow time in the next control code. One of the teams working on the airplane will be the regular crew of the new control code, the other is a special crew from the previous control code sent over to complete all remaining incomplete tasks from the previous control code. Manufacturing management monitors very closely these incomplete jobs, called "travelers." Thus, the prevailing attitude within manufacturing is to meet the schedule and avoid having to move incomplete jobs.

### **Manufacturing Flow Time Cost Visibility**

In Boeing's management accounting system, there has been little recognition of cost associated with manufacturing flow time. The lack of flow time cost

visibility, coupled with the importance of completing jobs to schedule (while maintaining the capability to manage unforeseen disruptions) and close management scrutiny on work-force head count, all contribute to the practice of managing the work-force head count, at the expense of manufacturing flow time. Consequently, as the total labor required within a control code decreases because of worker learning, the production planning methodology relies heavily on head-count reductions to realize learning-curve benefits; at the same time the methodology maintains flow time to insure that control codes can meet the strict production schedules and accommodate unforeseen disruptions.

We suggest that there are tradeoffs between the work-force level and the flow times. For instance, increases in labor head count and/or capital investments may be more economical ways than increases in the flow time to protect against unforeseen disruptions. In the proposed methodology, we explicitly examine the tradeoffs between the work-force level and flow time.

### **Flow Time Cost Elements**

There are three types of costs associated with manufacturing flow time: 1) inventory carrying cost, 2) revenue opportunity cost, and 3) variable tooling cost.

#### **Inventory Carrying Cost**

The first type of flow time cost is the inventory holding cost for carrying the value of the work-in-process (WIP) inventory for the duration of the control code flow time. The inventory holding cost includes the opportunity cost for the money tied up in the inventory, plus storage costs, insurance, spoilage and obsolescence costs. Usually, the inventory holding cost is computed as the product of the inventory value and an inventory carrying rate, which includes at least the opportunity cost for money. For instance, in Figure 3 we show a cumulative product cost curve for a hypothetical plane. This curve shows how costs are added to the plane over the flow time for completing the plane. The inventory holding cost for a plane is found by multiplying this

curve by the inventory carrying rate and then integrating over the total flow time for the plane.

We see from the example in Figure 3 how flow time effects inventory holding cost; a reduction in flow times will change the cumulative product cost curve, and presumably reduce the inventory holding cost per plane. Thus, the first type of flow time cost is the inventory holding cost for the work-in-process.

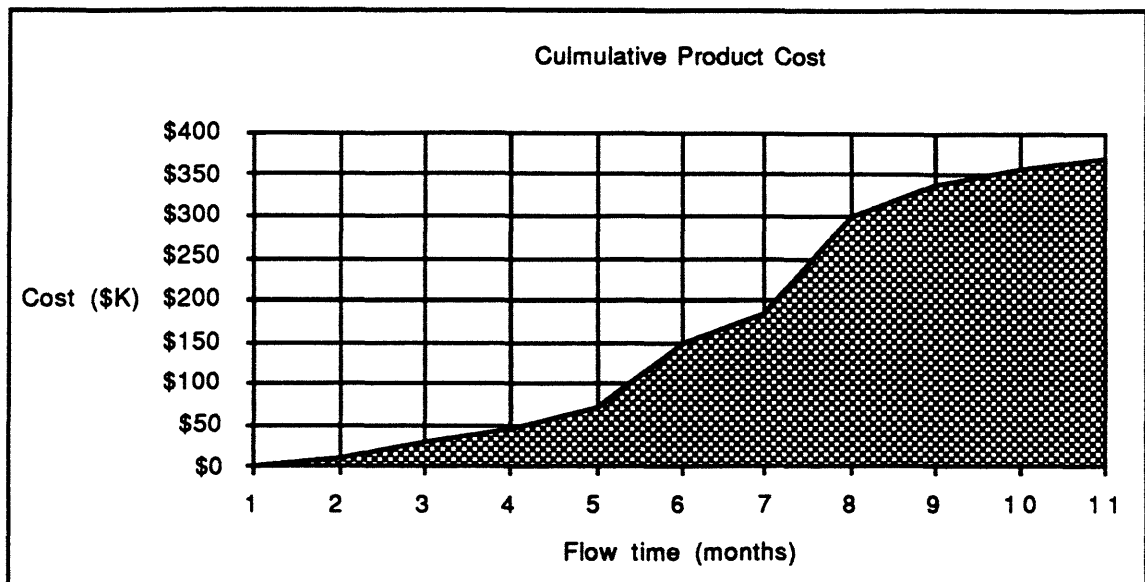


Figure 3: Cumulative Product Cost Curve for an Airplane

### Revenue Opportunity Cost

In a market where there is substantial demand backlog for a company's product, there is a second type of cost called revenue opportunity cost. Boeing commercial airplane group currently has an \$90 billion, three year order backlog<sup>1</sup>. Revenue opportunity cost is the potential revenue from collecting sales revenue earlier if a shorter flow time results in earlier delivery of orders. For example, in 1990 in the airplane industry, demand for airplanes

<sup>1</sup>Boeing News (November 1992).

exceeded supply<sup>2</sup>. An airline ordering a Boeing 747-400 in 1990 was not going to get delivery of the airplane until approximately 1997. With airline passenger traffic predicted to grow at over 4% annually for the next decade<sup>3</sup>, airline customers were eager to take delivery of newly designed, fuel efficient airplanes as quickly as possible. Given this market environment, there were significant revenue opportunity benefits associated with shorter product flow time (and earlier product delivery).

### *Flow Through vs. Flow Back*

Before we calculate the revenue opportunity benefit of shorter flow time, let us first discuss two possible implementations of flow time reduction. Consider a control code with eight days of flow time and a four day production rate, and suppose it reduces its flow time by one day. Implemented in isolation, the one-day flow time reduction at the control code brings about no tangible benefits to the operation. This is because the one-day flow time reduction has simply created a one-day buffer inventory at the particular control code if there are no other schedule changes to the adjacent control codes. To realize the benefits of flow time reduction, either the upstream control codes need to delay their schedules to absorb the one-day flow reduction, or the downstream control codes need to accelerate their schedules to avoid the creation of a one-day buffer. We term these responses as "flow back" or "flow through," respectively.

By "flow back," we push the one day reduction *back* through all upstream control codes. If the specified control code now has a seven day flow time, instead of eight days, then it can receive its jobs one day later and still meet the original delivery schedule. Thus, the output schedule for the immediate upstream control code can be delayed by a day, which allows it to receive its jobs one day later, and so on. Thus, the one day reduction in flow time allows all upstream control codes to shift their schedules by one day. The primary benefits are savings in inventory holding costs, as discussed in the previous section.

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<sup>2</sup>This was true at the time of the thesis (late 1990). With today's (1992) difficult market conditions, there are delivery positions available for interested airline customers.

<sup>3</sup>Boeing News (1990).

By “flow through”, we push the one day reduction *through* all the downstream control codes in the manufacturing process. To accomplish this, all of the control codes downstream of the specified control code must compress their schedule by one day on the very first airplane when the flow through is to occur. That is, these control codes will receive this very first plane one day earlier than planned, namely three days after the previous plane instead of the normal cycle of four days. These control codes need to complete their jobs within their normal flow times, and thus, they deliver the plane to the next control code one day ahead of the original schedule. After this very first plane, the schedules for all subsequent control codes are thereby advanced by one day. However, since there are no changes in either the flow time nor the production cycle time for these control codes, these control codes simply experience a one day compression when the flow time reduction flows through for the first airplane; after that, the control codes should continue to operate as normal, but one day ahead of the original schedule.

#### *Flow Through Illustration*

We have constructed a simple production schedule for a hypothetical sequential job shop in Figure 4 to illustrate how flow time reductions can flow through the manufacturing process. From the figure, we see that the manufacturing process is operating at a three-day production rate and consists of three sequential control codes, A, B, and C, with flow times of five days, four days, and five days, respectively. Note that for the first two jobs in the production schedule, a new job is started and a completed job is shipped out every three days. Suppose that there is an opportunity to reduce the flow time at control code A from five to four days. How do we flow through this flow-time reduction?

Table 1 below lists the start and completion dates for each of the control codes for all five jobs. On job number four, where the flow time buffer is actually taken out of control code A, control codes B and C had to accelerate their production schedules to “flow through” the flow time reduction (the dates in parenthesis listed in Table 1 are the original start and completion dates for each control code under the previous, longer flow time). We see from Figure 4 and Table 1 that after the one time schedule acceleration to flow

through the flow time reduction for job number four, control codes B and C settle back to their regular production pace, starting and completing each job one day ahead of the old schedule.

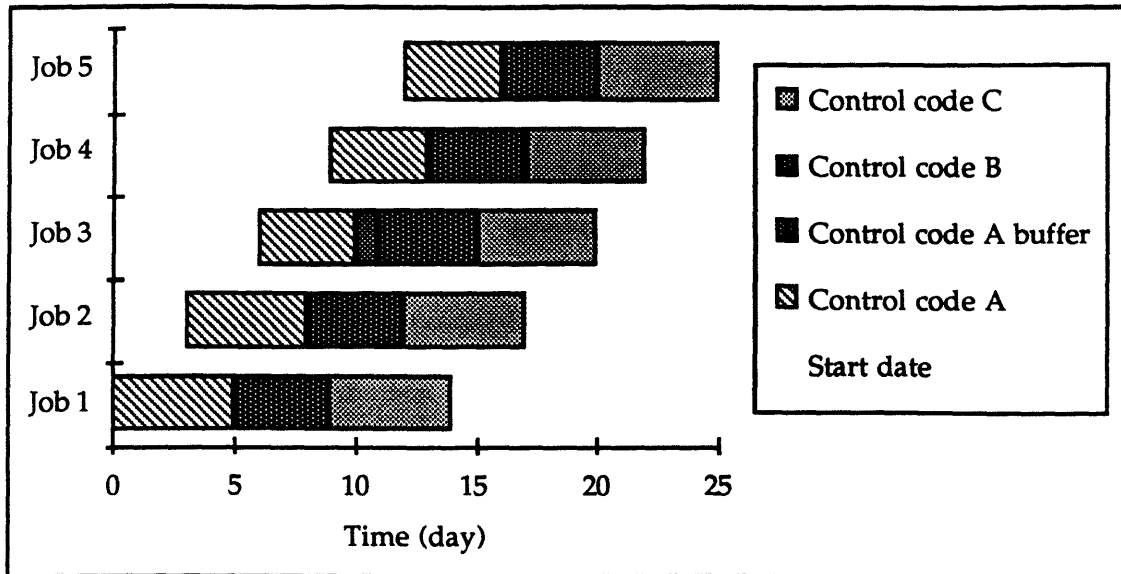


Figure 4: Production Schedule to Illustrate "Flow Through" Concept

	Control Code A		Control Code B		Control Code C	
	Start Date	Completn Date	Start Date	Completn Date	Start Date	Completn Date
Job 1	0	5	5	9	9	14
Job 2	3	8	8	12	12	17
Job 3	6	10	11	15	15	20
Job 4	9	13 (14)	13 (14)	17 (18)	17 (18)	22 (23)
Job 5	12	16 (17)	16 (17)	20 (21)	20 (21)	25 (26)

Table 1: Start and Completion Dates for Five Jobs in Production Schedule

This analysis applies similarly to a more complicated manufacturing process involving an assembly network of control codes (e. g. Figure 2). The control code, where flow time is reduced, must be on the critical path for the network. Then the schedule needs to be accelerated for all control codes downstream of the specified control code, and for all control codes on



branches that join into the critical path downstream of the specified control code. This is necessary in order to move the delivery schedule forward by the amount by which the control code's flow time has been reduced.

#### *Advantages and Disadvantages of Flow Through versus Flow Back*

A company can choose to flow back or flow through the buffer created by the flow time reduction. Flow back simply requires that upstream control codes start later; there is no compression of the schedule and implementation is far easier than flow through. Since there is no change to the delivery schedule for the final product, the only savings are the reduction in inventory carrying costs due to a shorter flow time. Flow through shifts the production schedule ahead by the length of the flow time reduction, and achieves revenue opportunity cost savings as well as inventory carrying cost savings. For a manufacturing process involving an assembly network of processes, flow through is possible only for control codes on the critical path of the manufacturing process. By choosing to flow through a flow-time reduction, a company will have to accelerate the production schedule for a pre-selected job in order to flow the inventory buffer through the manufacturing process. This requires both careful planning and additional manufacturing costs, such as overtime, to accomplish the acceleration of the pre-selected job. Once this is done, all subsequent jobs follow the original schedule, shifted forward by one day.

#### *Calculating Revenue Opportunity Cost*

Calculating revenue opportunity cost for an airplane program requires knowledge of present production cycle rate, selling price of the aircraft, customer pre-payment factor (if applicable), and relevant interest rates or the firm's cost of capital. Consider an example for a plane with a sales price of \$50 million. Suppose that there is no pre-payment factor and that there currently is a multi-year backlog for this plane. Customers make their payment at the time of delivery and are willing to accept (and pay for) early delivery. The company is operating at capacity and produces one plane every four days.

The company is considering a proposal to reduce its product flow time by one day. If the company flows the flow-time reduction through the

manufacturing process, it will then ship product to each of its customers one day earlier. From a cash flow standpoint, this will enable the company to collect its \$50 million revenue from each customer a day earlier than under the current, longer flow time. This shift in the revenue stream generates revenue opportunities for the company in the form of either simple interest or internal investments. For instance, at an annual interest rate of 10% and a working calendar of 250 working days per year, one (working) day of interest on \$50 million is \$20,000. Over the course of a year, with a four-day production cycle, the revenue opportunity from the one-day flow time reduction amounts to \$1.25 million. This savings of \$1.25 million per year will recur for the life of the plane's backlog. Furthermore, any additional reduction in the flow time that can flow through the process will generate revenue opportunity savings of \$1.25 million per year for each day. And any flow-time reduction, regardless of whether it flows through or back, yields savings in inventory carrying costs.

#### Variable Tooling Cost

Variable tooling cost is especially important in a high capital, labor intensive manufacturing environment such as at Boeing. This type of cost results from the purchase and maintenance of production tools and equipment for the manufacturing process. As noted previously, the number of job or tooling positions required in a control code is the flow time divided by the maximum cycle time, rounded up to the next largest integer. We will illustrate how tooling costs depend upon flow times.

A control code with eight days of flow time and a four-day production cycle requires two tooling positions. If the production rate increases to a three-day production cycle, the number of required tooling positions increases to three and a new tool has to be purchased, say at a cost of \$1.2 million. However, if the control code can reduce its flow time to six days, then the tooling requirement for the control code remains at two when the production cycle decreases from four to three days. Therefore, in this example, flow-time reduction from eight to six days saves \$1.2 million in tooling costs.

Variable tooling cost (and savings) increases in fixed increments that depend upon the production cycle time and the flow time for the control

code. For instance, in the example , a one-day flow time reduction bringing the control code flow time to seven days, is of no value in terms of the variable tooling cost when the production cycle changes to three days; the number of required tools at the control code is three for flow times of seven, eight or nine days. On the other hand, if we can reduce the flow time at the control code to six days, we no longer need to purchase the additional tool for the third position. Thus, a one-day flow time reduction has no variable tooling benefit in this example, whereas a two-day flow time reduction saves \$1.2 million in variable tooling saving.

### Intangible Elements of Flow Time Cost

In addition to the three types of flow-time cost, there are intangible costs as well. Long flow times in the manufacturing process lengthen feedback on production problems and allow these problems to accumulate in work-in-process inventory. Because of this, these problems require more corrective efforts to resolve and more rework to restore the work-in-process inventory.

In addition to lengthening the feedback process and increasing rework, long flow times also decrease a company's capability to respond quickly to shifting market demand. Because of long manufacturing flow time, a company becomes very dependent on accurate sales forecasts in order to produce products demanded by the market. If, however, market demand shifts unexpectedly, a company with long manufacturing flow time will be caught producing plenty of unwanted products and will require a longer period of time to bring in-demand products to market than competitors with short manufacturing flow times.

### **Implications of Flow Time Cost on Production Planning Methodology**

We have identified three components of the cost of flow time, and have shown how these costs can be evaluated in an environment like airplane assembly at Boeing. There has been limited visibility and awareness of these costs in the planning methodologies practiced at Boeing. In this section, we discuss two immediate implications to Boeing's production planning methodology that result from an awareness of flow time cost. We first use an example to show how flow time cost affects the joint determination of the

'optimal' staffing level and the flow time for a control code. We then discuss how the realization of productivity improvements changes in light of flow time costs, again with an example.

#### Determination of Control Code Design Parameters

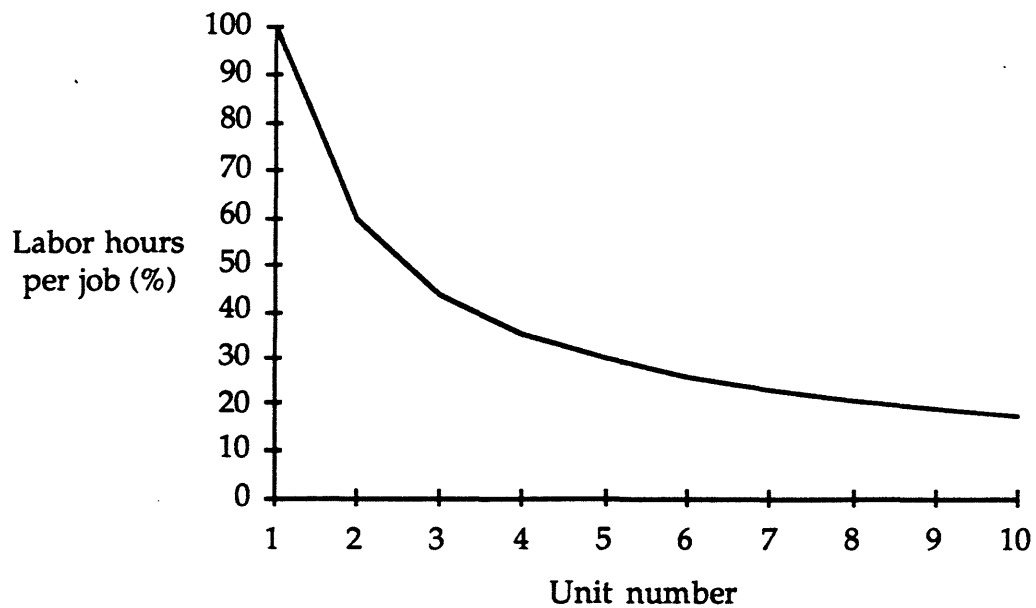
In determining the flow time and the staffing level for a control code, production planning needs to adapt its methodology to evaluate all relevant costs. The present methodology focuses on labor efficiency and capital investment, but does not properly incorporate the costs of flow time.

For example, consider a control code with a ten-day production cycle, a twenty-day flow time, and with a total staff size of six. The labor input is 480 hours per job. The present operation minimizes labor input per job by operating with the optimal crew size while protecting the schedule by having two jobs in process for smoothing unforeseen disruptions. Now, consider a proposal to reduce two days of manufacturing flow time at the control code by adding two more workers so that the labor input is 640 hours per job.

The present production planning methodology would view the flow time reduction as a bad proposal because of the increased labor cost per job. However, by incorporating flow time cost elements, this proposal might actually be very beneficial since it reduces inventory carrying cost at the control code by two days. In addition, if the flow time reduction can flow through the manufacturing process, the proposal would also bring about revenue opportunity cost savings.

#### Realization of Productivity Improvements

In a manufacturing environment where there is significant worker learning, the labor input required within each control code decreases as a function of the number of airplanes produced (see Figure 5).



**Figure 5: Sample Learning Curve**

As the labor hours decrease, the production planners have to decide how to utilize or realize these productivity improvements. Their options are to reduce the number of workers at the control code, or reduce control code flow time, or a combination of both. Because of past emphasis on head count as the primary tool of cost control, and due to the lack of flow time cost visibility, production planners have relied primarily on head-count reduction to realize these productivity improvements.

#### Proposed Production Planning Methodology

We propose a new methodology for utilizing worker productivity improvements that evaluates the possibility of reducing flow time. We illustrate this approach with an example.

Suppose a control code initially requires 100 labor-days, and operates with ten flow days and two tooling positions to meet a five-day production rate. There are twenty workers working in the control code, ten for each tooling position. Through worker learning, suppose the labor content decreases to about 10 labor-days by unit 256; however, because of manufacturing variances, labor content varies from plane to plane, and can

range up to 16 labor-days per plane. Assume that because of projected market demand, the production cycle rate is to increase to a two-day cycle. Table 2 lists three alternative scenarios of utilizing the productivity improvement benefits and their respective impact on flow time, labor head count and tooling positions.

From Table 2, we see that the three scenarios have drastically different labor content per job. In scenario one, where the control code has ten flow days and five job positions, the control code supervisor can shift workers between jobs (from easier jobs to harder jobs) and smooth the work variability between incoming airplanes [see Chao (1991) for more discussion of this point.]. In scenario three, where the control code has only two flow days and one job position, the control code supervisor must staff at a level capable of completing even the most difficult jobs within the production schedule; since the labor content per job can range up to 16 labor-days, the supervisor has to staff the control code with eight workers so that 16 labor-days are available per job. Scenario two is a mixture of the two extremes.

	Scenario 1	Scenario 2	Scenario 3
Flow Time	<b>10 days</b>	<b>6 days</b>	<b>2 days</b>
Cycle Rate	2 Days	2 Days	2 Days
Tooling Positions	<b>5 positions</b>	<b>3 positions</b>	<b>1 position</b>
Staffing	<b>5 workers</b>	<b>5-6 workers</b>	<b>8 workers</b>
Avg. Input / Job	<b>10 labor days</b>	<b>10-12 labor days</b>	<b>16 labor days</b>
Inventory Turns <sup>4</sup>	<b>126/5 = 25.2</b>	<b>126/3 = 42</b>	<b>126/1 = 126</b>

**Table 2: Three Different Ways to Realize Productivity Improvements**

To choose from these scenarios requires knowledge of the costs of flow time (inventory carrying cost; revenue opportunity costs; and variable tooling costs) as they apply to this control code, plus the cost of labor. More often than not this evaluation favors the scenario that reduces flow time the most, at the expense of labor productivity. This is counter to present practice,

<sup>4</sup>Inventory turn of control code calculated as annual output divided by average inventory. Annual output calculated as 252/cycle rate = 252/2 = 126.

which has not considered flow time cost and has focused primarily on minimizing labor content.

#### Implications of Proposed Methodology on New Airplane Program

In a new airplane program, where facilities have not yet been built, the proposed production planning methodology has significant impact. In particular, realizing productivity improvements via flow time reduction will result in significantly shorter flow times as the number of airplanes manufactured increases. Therefore, as the new airplane gains market acceptance and approaches maximum production rate, the shorter flow time will translate to lower facilities and tooling costs, in addition to substantially reduced inventory carrying cost and revenue opportunity cost. For a new airplane program, where new capital investments add up to hundreds of millions of dollars, the proposed production planning methodology can bring about significant program savings.

## IMPACT OF SYSTEM VARIANCE ON DIRECT LABOR INPUT

### Introduction

In the previous sections, we quantify the cost of flow time and examine the tradeoff between flow time and labor content within aircraft manufacturing. In this section, we consider how to avoid this tradeoff by attacking both flow time and labor content simultaneously. In particular, we analyze the impact of *system variances* on labor input, and indirectly on flow times. We define system variance as the “factors or elements within the manufacturing environment which affect the execution of baseline manufacturing operations.” Examples of variances in the manufacturing environment are engineering changes, part shortages, job rework, part rejections, and various product options.

During an internship at Boeing, the first co-author learned from interviews with manufacturing supervisors, shop workers, and industrial engineers that significant portions of total manufacturing labor input are attributable to system variances.

In this section, we present a working hypothesis regarding the effects these variances have on manufacturing labor input. We apply statistical methods, namely regression, to test the validity of the working hypothesis and to estimate the effects of the variances on manufacturing labor input.

### Working Hypothesis

We conjecture that for each control code there is a baseline work package that the control code is required to complete. Associated with this baseline work package is the baseline work time (BWT), measured in labor hours per job, which is a function of the complexity of the work to be performed and the number of airplanes manufactured thus far. The complexity of the baseline work package determines the initial time required to complete the tasks at the control code, while the number of units manufactured and the slope of the learning curve determine the actual baseline work time required for each airplane.



The actual manufacturing time spent by a control code to perform the required tasks differs from (usually greater than) the BWT. The workers at the control code, while working on the baseline work package, have to contend with external system variances such as engineering changes, part shortages, and rework that disrupt the process work flow and add extra work to the baseline work package. These system variances increase the labor input required by each control code to complete its operations.

We model the actual manufacturing time at each control code as the sum of the BWT and the cumulative effect of the various external system variances. We will test the validity of this working hypothesis by utilizing multivariate regression analysis to assess the effects of the manufacturing system variances on the actual manufacturing labor input.

### **Data Collection Methodology**

To test the validity of the working hypothesis, the first co-author studied the Boeing 7A7 airplane program and collected actual direct labor data and system variance data for fifty consecutive Boeing 7A7 airplanes. The direct labor hours were collected for major assembly for the manufacturing control codes for fifty consecutive Boeing 7A7s. Similarly, data from over thirty different sources of manufacturing variances were compiled for the same fifty airplanes.

### **Major Shops**

During data collection, we uncovered a difference in the way that data for direct labor hours and data for the system variances are kept. The direct labor hours are recorded and stored at the control code level, whereas the system variance data are collected, aggregated, and reported at the "major shop" level. These "major shops", which are aggregates of multiple control codes in the manufacturing process, are the major operational units of the manufacturing organization. The four major shops within the manufacturing sequence are: 1) Body structures, 2) Wing structures, 3) Join & Installations and Final Assembly, and 4) Field Operations.

To insure compatibility of data, we aggregated the labor hours data for the control codes by the four major shops. In addition, we aggregated all of

the data for the four major shops to form a data set for analysis at the airplane level. This was done in order to get a macro view of the overall impact of system variance effects on manufacturing direct labor input.

The actual labor input for manufacturing each airplane consists of direct labor plus several categories of indirect labor, such as rework. Because the data for the indirect labor categories are collected on a monthly basis rather than on a plane-by-plane basis, our analysis only considers the impact of system variances on the direct manufacturing labor hours.

### **Description of Regression Analysis**

The first co-author conducted the regression analysis for the Boeing 7A7 on StatView™, a statistical software package<sup>1</sup>. A total of five separate analyses were run for the Boeing 7A7 program. The first analysis is the regression of direct labor hours against about 30 system variances for the total airplane, and provides an analysis of variance impact on the entire 7A7 manufacturing process. The other four analyses are for assessing variance impact on each of the four major shops in the manufacturing process. We will report here only the results from the total plane regression; the regression results for the four major shops are similar to that for the total airplane but differ according to differences in the operating characteristics of these shops. Chao (1991) provides a full report of these studies.

In order to build an accurate model of direct labor hours, the first author consulted extensively with senior managers and industrial engineers at the Boeing Seattle facility. This consultation helped to determine the relevant manufacturing variances to include in the regression analyses, as well as to insure that the results of the analyses made sense and were consistent with their experience. Initial efforts attempted to regress over thirty different system variance variables as independent variables against the dependent variable, direct labor hours. This approach resulted in unsatisfactory solutions because many of the independent variables were correlated.

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<sup>1</sup>Abacus Software, Berkeley, California.

From this experience, the first co-author conducted a new round of interviews with industrial engineers, manufacturing managers, shop superintendents and factory managers to ask them what variables had the most impact on the manufacturing labor in each of the four major shops. The input from these individuals helped to prioritize the list of variances to form the starting set of variables for the new statistical analysis.

To complement the new starting set of variables, we used the stepwise regression feature in StatView™. Stepwise regression iteratively adds (or deletes) one variable at a time to the regression model, where the method selects the variable that will yield the largest reduction in the amount of unexplained variability in the model. Using this method, along with the smaller starting independent variable set, we were able to develop a satisfactory model for each major shop and for the airplane as a whole.

### Assessing Surprising Results

This methodology worked well except for a few instances when the regression results defied reasonable expectations and experience (for example, a model suggesting that rejection tags actually reduce manufacturing labor input). In these instances, we first examined the cross-correlation matrix of the independent variables to determine if there were any significant correlations among these variables and to determine if these variables were actually tracking the same system variance. If this was the case, Boeing engineers and managers were consulted to determine which of the variables to keep in the analysis, and the regression was re-run. In one case in which there were not correlated independent variables, a non-intuitive result was explained by the discovery of an outlier in the data base, namely a one-time only problem with a malfunctioning airplane engine that significantly increased the labor hours for that airplane. This outlier was handled by adding a dummy variable.

### **Statistical Regression for Total Airplane**

The details on the five regression analyses for the Boeing 7A7 can be found in Chao (1991). We will discuss the regression results for the total airplane, as an example. We aggregated the direct manufacturing labor hours and the

associated system variances for all four major shops to form a data set for the entire manufacturing process. While the aggregation of the data may cause loss of detail in the analysis, this regression should give us some sense of the variances that most affect direct manufacturing labor input on the production line.

In Table 3 we give the regression results, namely the independent variables, their coefficients and their standard errors for the model found by the regression. We will define the variables below. We do not report the intercept for the model, as calculated by the regression; the intercept represents an estimate of the direct labor hours for the first plane, and hence is proprietary.

Variable	Coefficient (labor hour/occurrence)	Std. Err
Customer introduction	2964	769.7
Part Shortage	3.6	1.0
Production Revision Request	276.7	28.3
Model 200	-2247.8	878.4
Defects	1.3	0.46
log <sub>2</sub> (x) of Unit number	-47732.6	8117.8

**Table 3: Regression Results for Total Airplane**

The top-level airplane regression provides a very good model, explaining 96% of the variability in the dependent variable, direct labor hours ( $R^2 = 0.96$ ). Furthermore, all of the variables in the regression are consistent with our prior expectations.

The *customer introduction* variable is a binary variable, which denotes that a particular airplane is being delivered to a new airline customer. This usually requires quite a bit more direct manufacturing input because of the learning required to satisfy the custom specifications for the first airplane for a new customer. In addition, during the customer introduction process, the airline customer is usually more exacting in inspections and thus requires more time during the acceptance process. From the regression, we see that a new customer results in nearly 3000 additional direct labor hours.

The *part shortage* variable denotes the total number of occurrences per plane where a part needed on the line is not available for installation. The *production revision request* variable is the number of requests generated by the manufacturing or engineering organizations to revise the manufacturing plan of an airplane; the variable only counts requests that require at least 100 labor hours and are subject to management review. These variables add to the manufacturing effort required to assemble and test the airplanes, as indicated by the positive regression coefficients.

The baseline airplane model of the regression, because of its popularity in the fifty plane sample, is the 7A7 model 300 (7A7-300). The model 300, which is approximately thirty feet longer than the model 200, requires more assembly and integration time than the model 200. The *model 200* variable is a binary variable that takes a value of one for model 200 and a value of zero for model 300. As expected, the regression model indicates that the model 200 airplanes require 2200 less labor hours to manufacture.

The *defect* variable counts the number of occurrences of correctable rejectable conditions on an airplane, as detected by the Quality Assurance department. Defects are usually considered to be relatively insignificant in terms of their overall effect on total manufacturing hours. From the regression model, we find that each defect adds only 1.3 labor hours. However, the appearance of defects as an explanatory variable in the regression suggests that defect rework labor is a significant part of the total direct labor hours expended in the manufacture of airplanes.

Finally, the *Log 2 of Unit Number* variable captures the learning effect. The independent variable is the log, base 2, of the cumulative production

number of the plane; for instance the thirty-second plane produced by the line would have a value of five for this variable. The regression coefficient for this variable signifies by how much the direct labor hours per plane go down when the production count doubles. As expected, we see a strong learning effect for the total manufacturing labor input as a function of the number of airplanes produced.

The traditional learning curve model assumes that the labor content goes down by a fixed percentage when the cumulative production count doubles. Here, we assume that labor content goes down by an absolute amount when the cumulative production count doubles. For both the total airplane and the four major shops, this learning model works quite well in terms of model fit; furthermore, it permits us to maintain a linear model that can accommodate the effects from system variances.

#### Construction of Variance Pie Charts

From the statistical analysis, we can construct a "variance pie chart" to show the relative impact of system variances on direct labor hours. In particular we determine what percentage of the total direct labor hours are due to each of the system variances from the regression. For instance, from the regression for the total airplane, suppose that the average number of defects per plane is 100. Then, each plane had an average of 130 labor hours due to defects; if each plane had an average of 5000 direct labor hours in total, then defects are responsible for 2.6% of the direct labor. In this way, we use the regression results to determine the relative contributions of the system variances to the total direct labor and to identify the high impact "vital few" variances. We have found that displaying these percentages with a pie chart is a very effective way to highlight the most important system variances. We constructed variance pie charts for the four major shops and the entire airplane final assembly process of the Boeing 7A7 airplane. We do not include these charts due to the propriety nature of these data.

#### **A Flow Time Reduction Strategy**

The regression analyses show that, consistent with Pareto principle, a few variances account for the majority of the impact on the direct manufacturing

labor input for the assembly of airplanes. Simply presenting these results, however, has little practical application since these results do not always point to particular strategies for reducing the level of these variances.

In the regression analysis, one variance in particular, defects, accounted for a significant portion of direct manufacturing labor input. Individually, each defect required relatively few direct labor hours to correct; in aggregate, however, defects accounted for a large portion of the total manufacturing labor input for the 7A7 airplane program. To develop a strategy for reducing defects, we were able to show that the engineering organization has a major effect on the level of defects and thus, plays an indirect role in determining the total direct labor input.

### Working Hypothesis

The engineering organization is responsible for two sources of system variances, engineering changes and rejections due to engineering error. Engineering changes and engineering rejections affect direct labor input both by creating rework and by disrupting the normal work flow in a control code. But these engineering variances also affect direct labor in another way. The disruption effect of these variances increases the likelihood of worker error (i.e. defects). Engineering changes and rejections cause changes in the nature of the pre-assigned tasks in the control code; their presence forces shop workers to consult with their supervisors or review new drawings to determine the proper actions to take for these variances. These disruptions increase the probability that shop workers will make errors during the assembly process either due to misinterpretation of the revised drawings or due to misunderstanding of the instructions given them. To test this hypothesis, the first co-author ran a regression analysis of defects as a function of numerous engineering variables. The results are given in Table 4.

Variable.	Coefficient (defect per occurrence)	Std. Err
Engineering rejections	3.75	1.2
Completed greenlines	3.79	0.38

**Table 4: Regressions Results for Defects**

The regression establishes a relationship between the number of defects and two engineering system variances, and explains 75% ( $R^2 = 0.75$ ) of the variability in the dependent variable. *Engineering rejections* are rejectable conditions (i. e., does not conform to standard) that are attributable to engineering error. *Greenlines* are 'extended' rejectable conditions. Often when a rejectable condition is found on one plane at a control code, Quality Assurance will find that the condition is also present on several other planes that had previously passed through the control code. If so, these other planes get greenlines so that the necessary rework is performed.

This analysis suggests that engineering plays an indirect, but important, role in determining the amount of direct labor input required to manufacture airplanes through its impact on defects. Focusing engineering efforts on reducing engineering rejections and greenlines can decrease the level of defects and can improve labor productivity. Thus, conducting cause-effect analysis on defects establishes a significant correlation between defects and specific engineering measures, and between manufacturing performance and engineering actions.

The improved labor productivity (lower labor input) brings about three significant benefits: 1) lower direct labor cost, 2) decreased variable labor overhead, and 3) reduced flow time cost. The improved labor productivity can bring about reduced flow time cost because presently, a significant portion of the current flow time is allocated to variance-related activities. If the level of these variances can be reduced, the efforts required to correct these variances will decrease and the associated flow time presently allocated to



these variance-related activities can be taken out without incurring additional risk to the schedule.

### **Conclusion**

The regression analyses for the major shops and the total airplane manufacturing process support the working hypothesis that relates actual labor input to baseline work time and the effects of external manufacturing variances. Along with the cause-effect analysis for defects, these analyses offer lessons for improving productivity and flow time. The regression focuses improvement efforts on the high-impact variances instead of diverting attention onto all the variances. Eliminating or reducing these system variances leads to productivity improvements and opportunities for flow time reduction. Finally, engineering has an important indirect impact on direct manufacturing hours through the effects that the quality of engineering release has on high-impact variances such as defects.

## IMPACT

This research generated three major recommendations for Boeing. The first recommendation is to *recognize the cost of flow time* as part of total cost, and to incorporate this cost into decision making at all levels. The second recommendation is to *implement a strategy for flow time reduction* throughout the manufacturing process. In the near term, this strategy is to consider flow time reduction as one means for realizing the benefits from learning in the manufacturing process, and to evaluate the tradeoff from flow time reduction versus the alternative of headcount reduction. In the long term, the strategy is to focus improvement efforts on eliminating system variances and improving the quality of engineering releases to manufacturing. The benefits from these longer-term activities will be less direct labor, less overhead and shorter flow times. The final recommendation is to *adjust the incentive system to motivate flow time reduction*. This includes putting the cost of flow time in the operating budgets for the manufacturing divisions and including flow time as part of the performance objectives for all levels of management.

At the completion of the research, the first co-author presented the findings and recommendations to numerous management teams at all levels of the organization. The response from Boeing management was very positive; as the research was conducted with the cooperation of senior management and involved participation of numerous Boeing organizations, there was considerable support and ownership for the recommendations.

As a result of these meetings, a planning directive was issued to take specific actions on these recommendations. First, a second study was performed on the 7B7 program to determine the impact of manufacturing variance on labor productivity, and thus replicate what had been done on the 7A7 program. The finance department was assigned to quantify the flow time cost for each flow day in the manufacturing process for the 7A7 and 7B7 programs. Finally, the manufacturing organization at the facility (which assembles both the 7A7 and 7B7) was asked to initiate and implement flow time reductions for the two airplane programs.

From these efforts, Boeing has achieved significant benefits. The manufacturing organization has removed several days of flow time from the 7A7

and the 7B7 programs. These reductions came primarily from converting the productivity improvements from learning into flow time reductions rather than headcount reductions. Some of the flow time reductions have been pushed through the manufacturing process to permit the acceleration of deliveries of airplanes. Within the first year, Boeing delivered one additional 7A7 and one additional 7B7 and collected the net profits from these additional deliveries. These reductions have also contributed to reducing work-in-process inventories and have generated net savings in inventory holding costs of tens of millions of dollars over a four year period.

More important than these immediate benefits is the fact that these efforts are continuing and the paradigm at Boeing for manufacturing planning is changing. Factory management and industrial engineering continue to drive the efforts to reduce flow time in the factory. The manufacturing organization recognizes the cost of flow time and it is being integrated as part of their planning methodology and their performance management system. Finally, the first co-author has joined Boeing and has the responsibility for inventory reduction for the next Boeing commercial jet, the 777; so these ideas and concepts are being applied on this new program.

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