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ANALYSIS OF VARIANCE IMPACT ON MANUFACTURING FLOW TIME

by

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ABSTRACT

The cost accounting system at Boeing does not emphasize 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 work station head count, encourage production supervisors to maintain flow time and minimize head count. In this thesis, I show that flow time is a significant manufacturing cost and that exclusion of this cost has resulted in production decisions that over emphasized head count reduction, at the expense of flow time.

I define flow time cost and examine three components of flow time cost: 1) inventory carrying cost, 2) revenue opportunity cost, and 3) variable capital cost. I show that including flow time cost in the management accounting system has significant implications on present production planning methodology.

After discussing flow time cost, I present a dual-prong strategy for flow time reduction. First, I propose a near term flow time reduction strategy through evaluation of potential trades of human and/or capital investments for immediate flow time reduction. This near term strategy reverses the effects of past production decisions that relied on head count to realize learning curve benefits. Next, I propose a far term flow time reduction strategy by evaluating the impact of system variances on manufacturing productivity. The analysis shows that for major shops within the manufacturing sequence, a number of "vital few" variances account for the majority of the effects on manufacturing productivity. Secondary cause-effect analysis shows that the Engineering organization has significant indirect impact on manufacturing productivity through its effects on these "vital few" variances. I propose an alternate resource allocation methodology based on the results of the statistical analysis.

Next, I examine the importance of modifying the current incentive system for motivating the organization towards continuous flow time reduction. Specifically, I propose that flow time cost be charged directly to the operating divisions and that it be incorporated as part of the management performance evaluation and reward system. I suggest that restructuring the incentive system to include flow time cost will motivate cross functional communication between the operations and engineering organizations and lead to significant near term and far term flow time reduction in the manufacturing sequence.

The above recommendations, formulated with the insights and experiences of numerous Boeing engineers and managers, were presented to Boeing management and have received strong support. A planning directive has been issued at Boeing's Everett plant to implement these recommendations.

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Chapter 1 INTRODUCTION

1.1 Background

Boeing is the world's most successful airplane manufacturer. In 1990, Boeing's family of commercial passenger airplanes[1] carried over 700 million passengers[2] to destination all over the globe. Boeing's over fifty percent market share of the worldwide airplane market continues to lead all other airplane manufacturers.

The competitive positions in the industry, however, are evolving. While Boeing's chief competitor had historically been the McDonnell Douglas Corporation[3], the past decade has seen the displacement of McDonnell Douglas from the number two position in the airplane market by Airbus Industries, a consortium formed by four European governments (England, Germany, France, and Spain). The financial support provided by these four governments to Airbus for the development and manufacturing of new airplanes has resulted in significant market gains for Airbus and made it a legitimate player in the industry. The rapid rate that Airbus has sustained in gaining market share during the 1980s highlights the importance that Airbus has placed on the commercial aviation industry and underlines its determination to become a key player in the airframe market.

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[1] The Boeing 707, 727, 737, 747, 757, 767 (the Boeing 777 will be introduced in 1994).

[2] Cruze, Deane. *Breaking Out of the Box,* MANAGER - Boeing Management Magazine, Mar-April 1990.

[3] McDonnell Douglas presently produces the MD-80, DC-10 and MD-11 airplanes.

Boeing though is not resting on its laurels. Current Boeing leadership is emphasizing the importance of continuous quality improvement (CQI) and has made it an explicit goal of the corporation to use CQI as the preferred way to improve product quality, customer service and corporate profitability. This commitment has also resulted in Boeing's participation in the Leaders for Manufacturing (LFM) program at the Massachusetts Institute of Technology. The Leaders for Manufacturing program, a joint effort between the Massachusetts Institute of Technology and eleven industrial partners[4] , has as its mission to educate future leaders for manufacturing and to improve U.S industrial competitiveness.

In this thesis, I present the results of my thesis internship at The Boeing Company. In June 1990, I started my internship at Boeing in the New Airplane Division[5] to conduct research for a joint engineering and management thesis for the department of Electrical Engineering and the Sloan School of Management. My Boeing advisor recommended that I study the Boeing 767 final assembly process at Boeing's Everett, Washington plant to assimilate lessons learned about 767 manufacturing and to make specific recommendations for the 777 program.

I conducted my study at the Everett plant from mid-July through mid-December of 1990. During those six months, I worked closely with various groups at the Everett facility (especially the Industrial Engineering group) and learned valuable lessons from the people around me. At the end of the

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[4] The industrial partners are Alcoa, Boeing, Chrysler, Digital Equipment Corporation (DEC), General Motors, Hewlett-Packard, Johnson & Johnson, Kodak, Motorola, Polaroid, and United Technology Corporation (UTC).

[5] The New Airplane Division is now known as the Boeing 777 division

internship, we (I and all the people at Boeing who generously gave their time and support) formulated a set of three specific recommendations based on our six month study. These recommendations, detailed in chapters 3, 4 and 5, should not only have a positive impact on the Everett plant, but on the 777 division as well.

1.2 Thesis Summary

In this thesis I present results of my six-and-half month research internship at The Boeing Company. I show that the traditional accounting system in use at Boeing does not consider flow time as a significant manufacturing cost. Current emphasis on schedule adherence, along with management focus on worker head count, encourage production supervisors to maintain or increase flow time and minimize head count. I show that flow time is a significant manufacturing cost and examine three specific elements of flow time cost. I analyze how flow time cost will affect present Boeing production planning methodology and propose an alternate methodology which incorporates flow time cost into the production planning and resource allocation process.

Next, I present a dual prong strategy for flow time reduction. I propose that flow time can be reduced in the near term through examination and evaluation of alternate flow time reduction proposals aimed at reversing the effects of past production decisions (which overemphasized head count reduction to utilize the benefits of worker learning, at the expense of flow time). These flow time reduction proposals, which may be investments in human and/or capital equipment, should be evaluated by the marginal cost

(cost of implementation, a one time cost) and the marginal benefit (flow time cost reduction, a recurring benefit) of individual proposals.

Interestingly, while the near term strategy increases corporate profitability (we would not implement flow time reduction proposals which do not contribute to improved profitability), it does not improve manufacturing productivity. To improve manufacturing productivity, I show, through my analysis of variance impact on manufacturing productivity[6], that we must reduce the frequency of occurrence of some "vital few" variances. I show that Engineering plays an important, albeit indirect, role in determining manufacturing productivity.

Finally, I suggest that the current incentive system be re-aligned to motivate organizational change. Specifically, I suggest that flow time cost be incorporated as a management performance objective and that it be charged directly to operating division budgets. I suggest that moving flow time costs to the level where they are actually incurred (and where their overall level are actually determined) will better focus divisional management attention on the relative tradeoffs between components of total product cost. Moving flow time cost responsibility to the divisional level thus empowers division management to make production and resource allocation decisions which are consistent with reducing total product cost rather than specific elements of total product cost.

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[6] Variance is defined as "factors or elements within the manufacturing environment that affect the execution of baseline manufacturing operations". See chapter 4 for detailed discussions.

1.3 Thesis Organization

A brief description of each of the remaining chapters in this thesis follows.

Chapter 2 Nature of Airplane Manufacturing

This chapter describes some of the methodologies used during production planning within Boeing's manufacturing organization. In particular, we look at production planning tools such as the number one flow chart, the master schedule, and the crew size studies. Readers familiar with the methodologies of the production planning process can skip this chapter and proceed directly to chapter 3.

Chapter 3 Flow Time Cost

In this chapter, I introduce the concept of flow time cost and detail three major cost elements: inventory carrying cost, revenue opportunity cost, and variable tooling cost. I go over each of these cost elements and give examples showing how to calculate these costs.

Next, I propose that future resource allocation evaluation criteria include flow time cost/benefits. I then examine how flow time cost visibility will affect current production planning methodology and propose an alternate methodology which better utilizes labor productivity improvements. Finally, I propose a near term flow time reduction strategy.

Chapter 4 Analysis of System Variance Impact on Direct Manufacturing Labor Input

In this chapter, I describe sources of system variances within an aircraft manufacturing environment and present a working hypothesis regarding the effects of system variances on manufacturing productivity. I detail the methodology of the statistical analysis used to analyze the effects of system variances on manufacturing labor input (additive model with input variances and associated sensitivities) and outline assumptions intrinsic within the analysis. Next, I present results of the statistical analysis.

This will be followed by a discussion of the results and the implication these results have for the work areas. Finally, I present a far term flow time reduction strategy.

Chapter 5 Role of Incentive Systems in Motivating Organizational Change

This chapter is devoted to how incentive systems can be structured to instill organizational impetus to initiate and sustain flow time reduction programs. I suggest that under the present incentive system, where process efficiencies are realized through labor reductions, there is a negative feedback to workers to improve the manufacturing process due to fear for job security. I show that under the proposed system, where productivity improvements are realized through flow time reductions rather than labor reductions, there will be positive feedback for workers and supervisors to renew focus on process improvements.

To further motivate efforts toward continuous flow time improvement, I recommend that flow time be added to manufacturing performance objectives. Specifically, I suggest that flow time be included as an operating division budget item.

Chapter 6 Conclusion

I open this chapter with a review of the recommendations made in the preceding chapters and detail actions Boeing management has taken to address these issues. Finally, I suggest some applications of the methodologies presented in this thesis to other industries.

Chapter 2 NATURE OF AIRCRAFT MANUFACTURING

2.1 Introduction

In this chapter, we discuss the nature of airplane manufacturing. Specifically, we describe the organization of the manufacturing processes for airplane assembly. We also review specific production planning tools such as the number one flow chart, the muscle charts, the master schedule and the crew size studies.

2.2 Description

The assembly of an airplane entails a series of manufacturing processes which are organized as a network of concurrent and merging flows. These manufacturing processes are in turn made up of operational work units or departments called control codes. These control codes, staffed with varying numbers of line employees, have responsibility for performing pre-assigned tasks within the manufacturing process. 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 control codes each perform specific, pre-assigned tasks on individual incoming jobs for a specified period of time called the manufacturing flow time.

Within the context of this thesis, manufacturing flow time[1] is defined as the time[2] required within a control code to perform required tasks. That is, the control code flow time is the length of time that an airplane will remain in a specific control code. The operations performed by these control codes varies 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. The time required by each control code to complete its pre-assigned tasks, however simple or complex, is defined as the control code flow time. Note that each control code within the manufacturing sequence can have a different flow time.

The production cycle time[3] is defined as the time[4] elapsed between consecutive job completions or airplane deliveries for a control code or for the entire manufacturing system, respectively. Unlike manufacturing flow time, all control codes within the manufacturing system must operate at one 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 in the manufacturing sequence must also complete work on an airplane every three days (no matter what the individual flow time of the control code is). So, every three days, an in-process job is completed by each control code in the manufacturing process. Correspondingly, every three days, a new job enters each control code in the

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[1] Within some industries, flow time is also known as cycle time or lead time.

[2] Time is measured in normal work days, known within Boeing as manufacturing days or M-days.

[3] Also known as production cycle rate. These two terms will be used interchangeably throughout the thesis.

[4] Also measured in normal work days or M-days.

manufacturing process. Note that a control code's flow time is often a multiple of the production cycle time, although this is not always the case.

Difference Between Flow Time and Cycle Time

To illustrate the difference between flow time and cycle time, consider a control code which has eight days of flow time and operates on a four day production cycle. In this case, the control code is given eight days to complete required tasks on each job and is required to ship a completed job out of the control code every four days. To do so, the control code must work on more than one airplane at a time. If the operations within the control code require special tooling positions, then more than one tooling position must be made available in order for the control code to work on each individual job for eight days and ship a completed job out of the control code every four days . Therefore, associated with control code flow time and production cycle rate is the number of job or tool positions required within each control code to operate within the given flow times and production rate.

The number of job or tool positions required within a control code given flow time and production rate is simply the quotient of the control code flow time divided by the production cycle time (job or tool position is equal to quotient plus one if the remainder of the division is non-zero). So, for the control code above with eight days flow time operating on a four day production cycle, the number of job or tool positions is equal to 8/4 = 2 positions. Thus, while there are always two jobs in process at the control code, each job spends eight days at the control code and a completed job is shipped out every four days (see Figure 1.) Similarly, for a control code with eight days of flow time operating on a three day production cycle, the number of job or tool positions is equal to (8/3 = 2) + 1 = 3 positions.

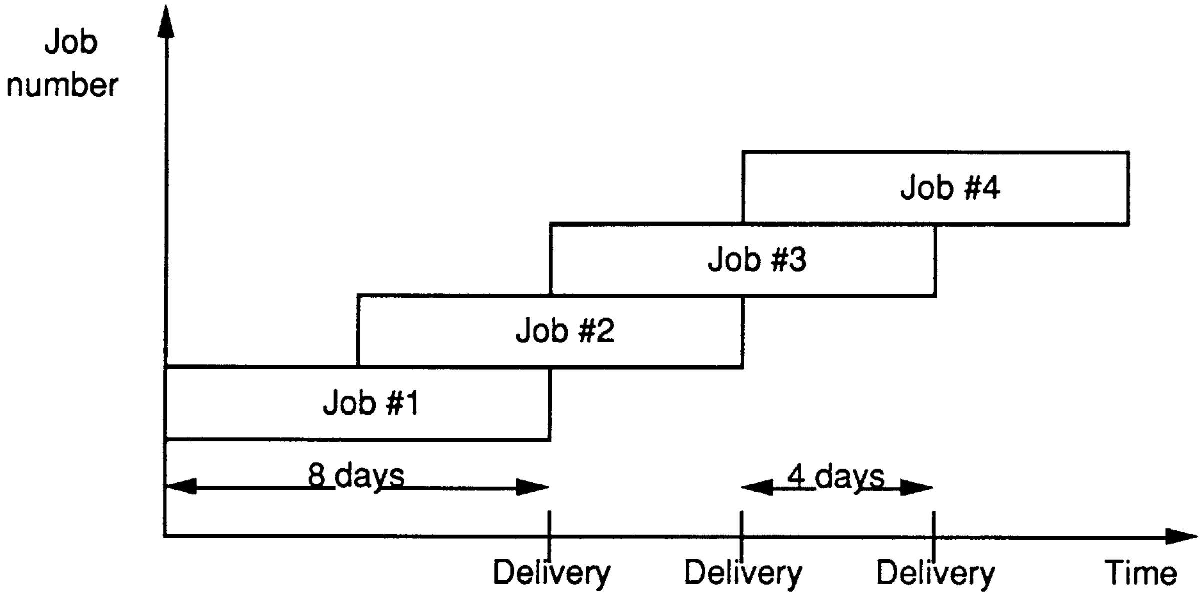

Figure 1: Illustration of Flow Time versus Production Cycle Time

Number One Flow Chart

The number one flow chart outlines the exact sequence of every control code in the airplane manufacturing process[5] (see Figure 2). 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 (note that in Figure 2, the length of the jobs equals the flow time for the control code).

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[5] There is a new number one flow chart for each new airplane program, model derivative, or new production rate.

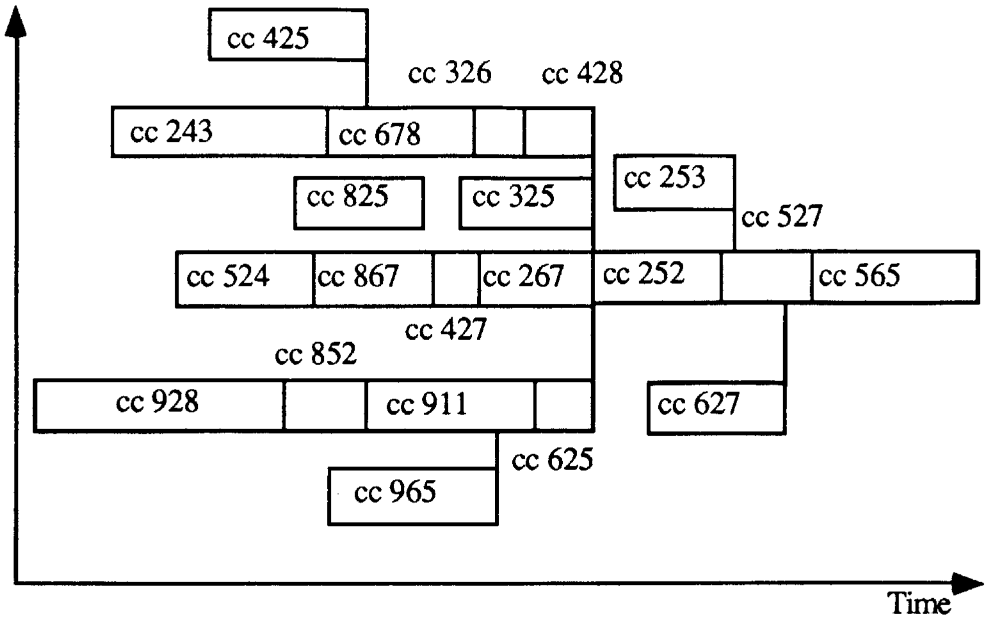

Figure 2: Sample Number One Flow Chart

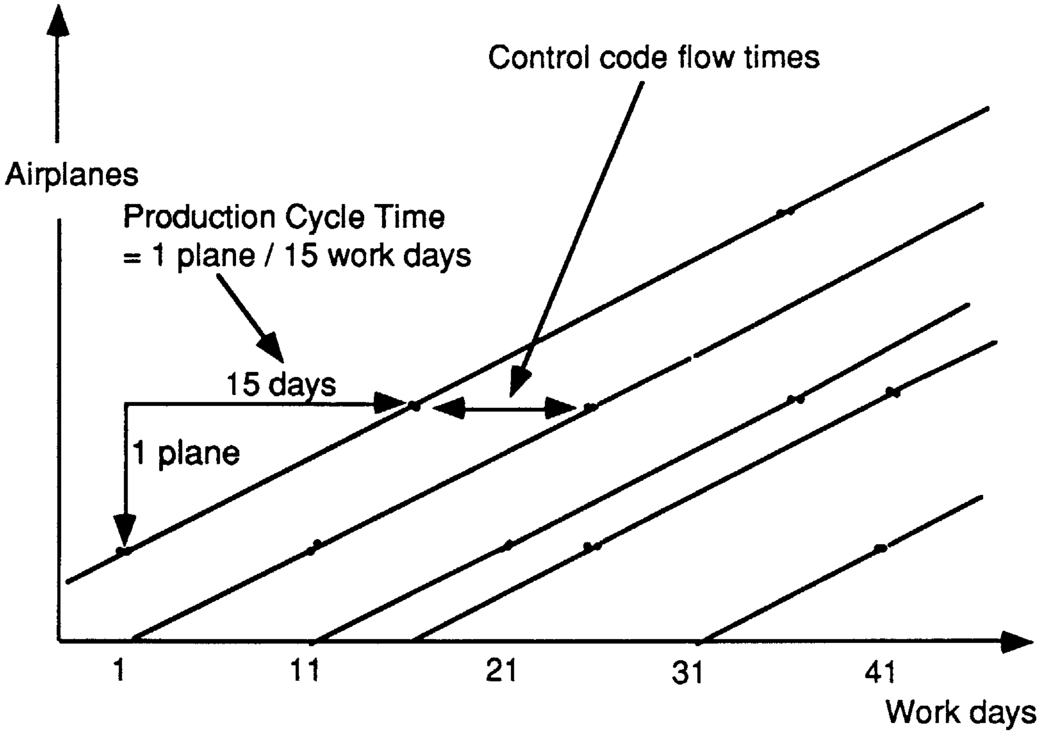

Figure 3: Sample Master Schedule

Master Schedule

While the number one flow chart outlines the sequence of control code operations for each airplane, the master schedule shows the sequence of control code operations for multiple airplanes. The master schedule is a graph depicting the status (control code and position load/unload) of every airplane in the manufacturing process for a specified time frame (see Figure 3).

As we see, the horizontal axis of the master schedule shows normal work days while the vertical axis of the master schedule represents specific airplane unit numbers. Each diagonal line in the master schedule represents a control code in the manufacturing process. A glance at the master schedule reveals a great deal about the production plan. First, the space between consecutive dots (called delivery points) for the same airplane represents the length of time that each airplane will remain in a specific control code (flow time). Second, the production cycle time is reflected in the master schedule as the elapsed time between consecutive airplane delivery points from the same control code (the production cycle time is thus the slope of the airplane delivery line). Third, changes in control code flow time are easily detected on the master schedule by examining the convergence or divergence of formerly parallel-running delivery lines (change of spacing between delivery points). Fourth, changes in the production cycle rate are easily detected on the master schedule by changes in the slope of the delivery lines. An increase in the slope of the delivery line (airplanes/time) indicates an accelerated production cycle. Similarly, a decrease in the slope of the delivery line indicates a decelerated production cycle.

Estimating Manufacturing Work Statements

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 respective sequences that these tasks must be performed in. The Estimating unit (part of the Industrial Engineering department) estimates the direct labor input required to complete pre-assigned tasks outlined in the manufacturing work statements by using one of two possible estimating methods: parametric estimating or detail estimating.

Parametric estimating is a methodology which uses specific product attributes (or parameters) such as weight, length, or performance to predict product cost. The sensitivities of these parameters to total product cost are determined by historical relationships through statistical regression analysis. This methodology is good for first cut, macro level cost estimates and is usually used to estimate costs for major sub-systems or an entire airplane. An example of parametric estimating could be to use labor hours per pound to predict airplane manufacturing cost; or, to use historical learning curve values and the number one unit hours (calculated by using the projected weight of the airplane to estimate the number one unit hours) to predict the labor hours required to assemble the one hundredth airplane.

The second methodology utilized by the Estimating unit is called detail estimating. Detail estimating is usually done for specific components where the required operations and related sequences can be determined beforehand.

As an example, a detail estimate of the drill operations needed for a complex machined part might be calculated as followed.

Detail Estimate for Drill Operations[6]

Get part from skid	0.1	min
Load on drill jig	1.25	min
Place plastic shield	0.15	min
Drill six holes	2.90	min
Put shield aside	0.1	min
Shaving to barrel	0.65	min
Blow off chip	0.15	min
Unload part from jigs	0.9	min
Put part on skid	0.2	min
Base time	6.4	min
Personal, fatigue and delay (PF&D) allowance of 15%	0.96	min
Standard time	7.36	min

Crew Size Study

The flow time of a control code is determined by the estimated work hours (calculated from the manufacturing work statement) and the crew size of the control code. The crew size of a control code is in turn determined by crew size studies conducted for each control code. The crew size studies analyze a total of four alternate control code crew configurations: minimum crew, optimum crew, maximum crew and peak crew.

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[6] From Industrial Engineering in the Boeing Commercial Airplane Company, p.66.

The minimum crew size is the minimum number of shop workers that should be stationed at a particular control code to sustain a minimal working production schedule. The minimum crew can be used during slow production periods to minimize the number of shop workers in the factory. The optimum crew size, which is larger than the minimum crew, gives the number of shop workers at the control code when individual worker productivity is maximized. This is the crew size where the direct labor input per job is at its lowest (because of the maximum individual worker productivity utilized by the given crew size).

The maximum crew size gives the maximum number of workers at a control code that can be "economically used to perform the production work."[7] The individual worker productivity at the maximum crew is lower than that at the optimum crew because the greater number of workers at the control code reduces available work space and impedes individual worker effectiveness.

The peak crew size, which is even larger than the maximum crew size, gives the number of workers at the control codes that can be utilized to minimize control code flow time. The peak crew size is determined as the number of shop workers where incremental worker productivity is zero (that is, adding another worker to the peak crew will not reduce the flow time of the control code.)

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[7] From Industrial Engineering in the Boeing Commercial Airplane Company.

Lifeline Study

For each control code, a lifeline study is performed to determine the minimum flow time necessary to perform pre-assigned tasks. The lifeline study is conducted with peak work crew and is used to analyze the bottleneck constraints of the pre-assigned tasks in the control codes (such as limiting sequential flow of process) which limits minimum flow. For example, in the "Clean, Seal and Paint" (CS&P) operation in the manufacturing process, peak crew can speed up some specific labor intensive aspects of the operation such as sealing and painting; however, the curing process for the sealing and painting operations are fixed for a given process regardless of the number of workers working in the control code. Thus, the curing time of the sealing and painting process would be included in the limiting flow of the control code lifeline.

An example

Now, let us integrate all the aforementioned tools in an example. Suppose that by using the manufacturing work statement, we estimate that for a particular control code the number one production unit (i.e. the very first airplane) will require eight hundred labor hours to assemble a plane at the control code. Assume that crew size studies determined that the optimal crew size is ten workers per job. The production line is currently operating on a five day production rate. Given these, how do we plan the production process for this control code?

Using present planning methodology, we determine that the number one unit flow time for the control code[8] is 800 hours/(10 workers * 8 hours per worker-day[9]) = 10 days. Given the five day cycle rate, we calculate that the number of tool positions required at the control code is equal to 10/5 = 2 positions. So, the control code will initially have twenty workers[10] at the control code working on two jobs for ten days each. The control code will complete work on a job every five days (see Figure 4).

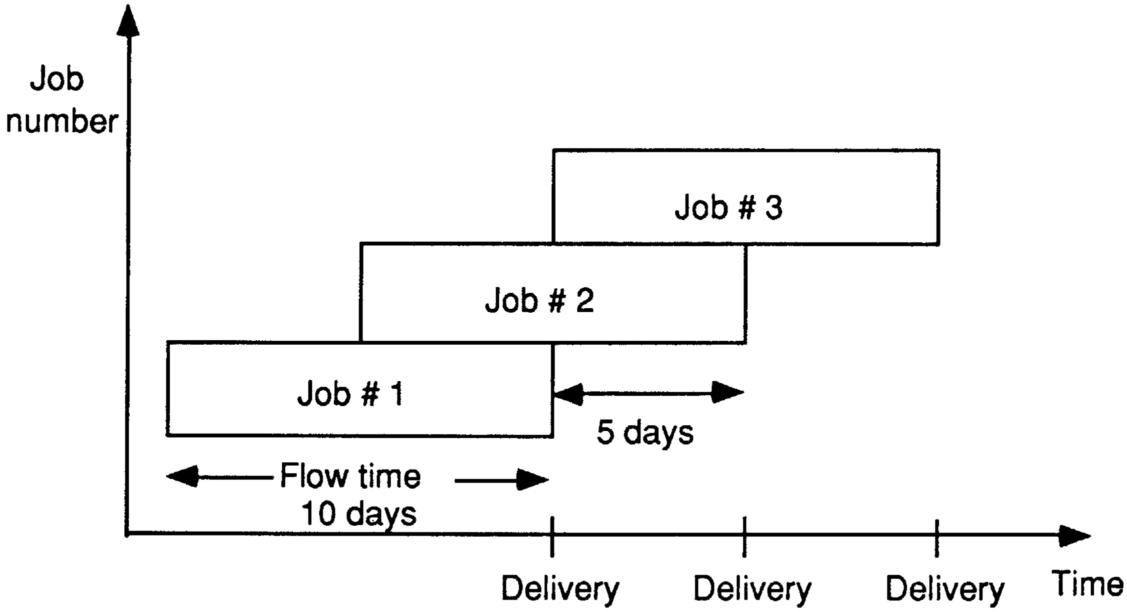

Figure 4: Sample Control Code Schedule

Now, because of improved worker productivity, suppose that the labor input per job has decreased from eight hundred labor hours per job for unit number one to eighty labor hours per job for unit number 256. How do we plan the production of unit number 256?

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[8] Using optimal crew size to minimize labor required per job.

[9] Assuming single shift operation.

[10] There are ten workers per tool position. Since there are two tooling positions, the control code has twenty workers.

For unit 256, we see that one possible scenario is keep the number of flow days at ten and to decrease the control code head count from twenty to (2 * (80 hours / (ten days * 8 hours per worker-day))) = 2 workers. With this scenario, the number of tools required remains at two. Alternately, we can decide to operate with five flow days in the control code and reduce the number of workers to (80 hours / (5 days * 8 hours per worker-day)) = 2 workers (see Figure 5). Notice that even though the number of workers remain the same, the number of tools required at the control code decreases from two to one. As we will see later, these two different scenarios have significant implications on total product cost.

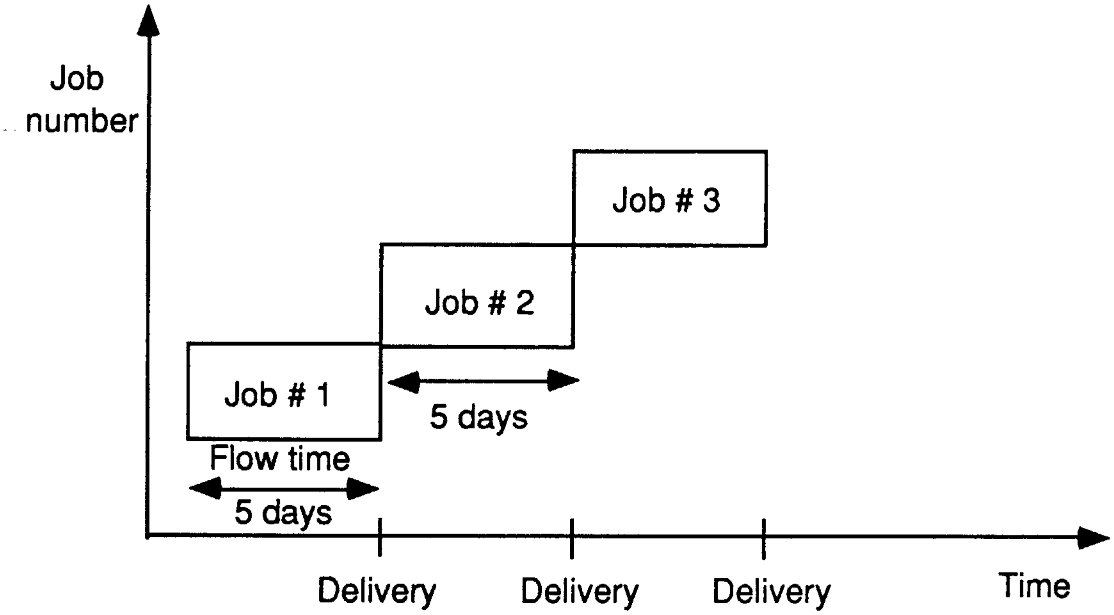

Figure 5: Sample Control Code Delivery Schedule

2.3 Organizational Impact on Production Planning

In the above example, we see that by using available planning tools differently, the production planning group can propose drastically different production plans that are responsive to management focus on labor productivity and schedule adherence. However, as we will show in the next chapter, maximizing labor productivity alone by staying at optimal crew (and the flow time implied by the optimal crew size) can actually decrease corporate profitability because of flow time cost.

2.4 Conclusion

As we see in this chapter, the process of planning and coordinating a complex production process such in an airplane manufacturing plant requires extensive knowledge, experience, and coordination. In this chapter, I 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 few chapters, we will see how lack of flow time cost visibility results in production plans that emphasized reduction of worker head count and preservation of manufacturing flow time. I show that these production plans, while successful in minimizing worker head count and assuring schedule adherence, sometimes resulted in longer process flow times and decreased corporate profitability.

Chapter 3 FLOW TIME COST

3.1 Introduction

In Boeing's management accounting system, there is presently no visibility of flow time cost. In this chapter, I present the motivation for understanding flow time cost and detail three primary components of this cost: 1) inventory carrying cost, 2) revenue opportunity cost, and 3) variable tooling cost. Next, I discuss how the lack of flow time cost visibility causes the present production planning methodology to over emphasize head count reduction at the expense of flow time and detail how these decisions adversely affect operational profitability. I then propose a near term flow time reduction strategy to reverse the effects of these decisions. Finally, I recommend that flow time cost be incorporated into the production planning methodology.

3.2 Motivation

Within Boeing management, adherence to schedule is considered paramount. This is partly due to the significant cost penalties involved when airplane deliveries are delayed. The sequential nature of the manufacturing process work flow 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. This is because the delay of a single job within the sequential manufacturing process could disrupt the work flow on the production line and postpone 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 offending 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. These incomplete jobs, called "travellers", are monitored very closely by manufacturing management. Thus, the prevailing attitude within manufacturing is to protect schedule jealously because of the huge cost involved. This philosophy has resulted in manufacturing practices which emphasize "Just-in-case" instead of "Just-in-time". One of the results of these practices is the lengthy flow time present in the current manufacturing process.

Manufacturing Flow Time Cost Visibility

In Boeing's management accounting system, there is 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 present practice of reducing work force head count while preserving manufacturing flow time. Consequently, as the total labor required to perform pre-assigned manufacturing tasks within a control code decreases because of worker learning, current production planning methodology relies heavily on worker head count reductions to realize learning curve benefits, while at the same time preserving manufacturing flow time in order to insure that control codes can adhere to tight production schedules and be protected against unforeseen disruptions.

This methodology, which does not fully take flow time cost into account during the production planning process (see section 3.3 for discussion on components of flow time cost), actually *increases* manufacturing cost significantly when applied within a high capital, high inventory environment such as Boeing's final assembly process. In this thesis, I propose an alternate production planning methodology, one which does take into account the cost of manufacturing flow time and still operates within the requirement of strict schedule adherence.

Specifically, I suggest that in most instances within the manufacturing environment, flow time buffering is not the only method available to protect against unforeseen disruptions. I suggest that in certain instances, increases in labor head count and/or capital investments are just as effective as flow time buffers in protecting against the effects of unforeseen disruptions. In the proposed methodology, we evaluate and compare production alternatives (such as increased labor head count and/or additional capital investments), which are comparably capable of protecting the production schedule from disruption, against the alternative of flow time buffering.

3.3 Flow Time Cost Elements

Given the definition of flow time in section 3.2, in this section I show that there are three significant elements of cost associated with manufacturing flow time. Specifically, I show that flow time cost is composed of three major cost elements: 1) inventory carrying cost, 2) revenue opportunity cost, and 3) variable tooling cost.

Inventory Carrying Cost

The first element of flow time cost is the opportunity cost of money associated with carrying the value of the work-in-process (WIP) inventory for the duration of the control code flow time. I call this opportunity cost the inventory carrying cost (recognizing that this cost is only a subset of the more general definition of inventory carrying cost which also includes the opportunity cost of carrying raw materials and finished goods).

The inventory carrying cost arises as follows. By having money invested in inventory, a company loses the use of its money for the duration of the manufacturing flow time. Since the minimum return of the company's money is simple interest (such as bank CDs), each flow day the work-in-process (WIP) inventory is being worked on in the manufacturing process costs the company, at the very least, simple interest expense on the full value of the WIP inventory[1]. Because inventory carrying cost is a function of inventory value, this component of flow time cost varies with

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[1] Inventory carrying rate should also include storage cost, insurance, spoilage and obsolescence, and overhead.

flow time as value is being added during each flow day of the manufacturing process (see figure 2).

Calculating Inventory Carrying Cost

Calculating inventory carrying cost for a manufacturing process requires detailed, precise information regarding cost-adding activities ongoing within the manufacturing process. Specifically, to calculate inventory carrying cost for each day within the manufacturing process, we must know the labor required to complete assigned tasks within each control code, the relative sequence of all control codes and the flow and costs of all parts and sub-systems into the manufacturing process. With this information, daily inventory carrying cost for each control code (and for each manufacturing day) can be easily calculated.

An example

Given a cumulative product cost curve (or value-added curve) as shown in Figure 1, how do we calculate the product's inventory carrying cost component of flow time cost?

We can calculate the inventory cost curve for this product for every flow day of the manufacturing process by making use of the formula below:

Inventory carrying cost for flow day t= WIP inventory at flow day t * inventory carrying rate

or, in simplified notation:

ICC (flow day t)= WIP (flow day t) * ICR (Equation 3.1)

Applying this equation for every point on the cumulative product cost curve[2], we get the inventory carrying cost profile as shown in Figure 2. Not surprisingly, we see that the inventory carrying cost curve has the identical shape as the cumulative product cost curve since the inventory carrying cost for a particular flow day is simply the cumulative product cost for that flow day multiplied by the inventory carrying rate. Note that Figure 2 is calculated in terms of inventory carrying cost *per plane*.

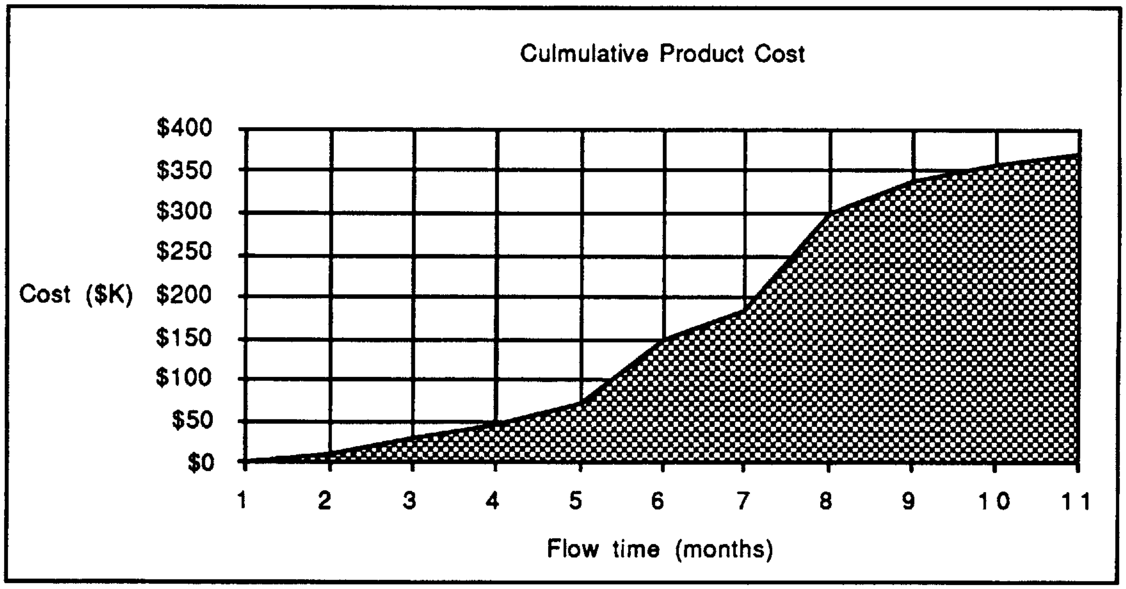

Figure 1: Cumulative Product Cost Curve

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[2] Assuming annual inventory carrying rate at 25%.

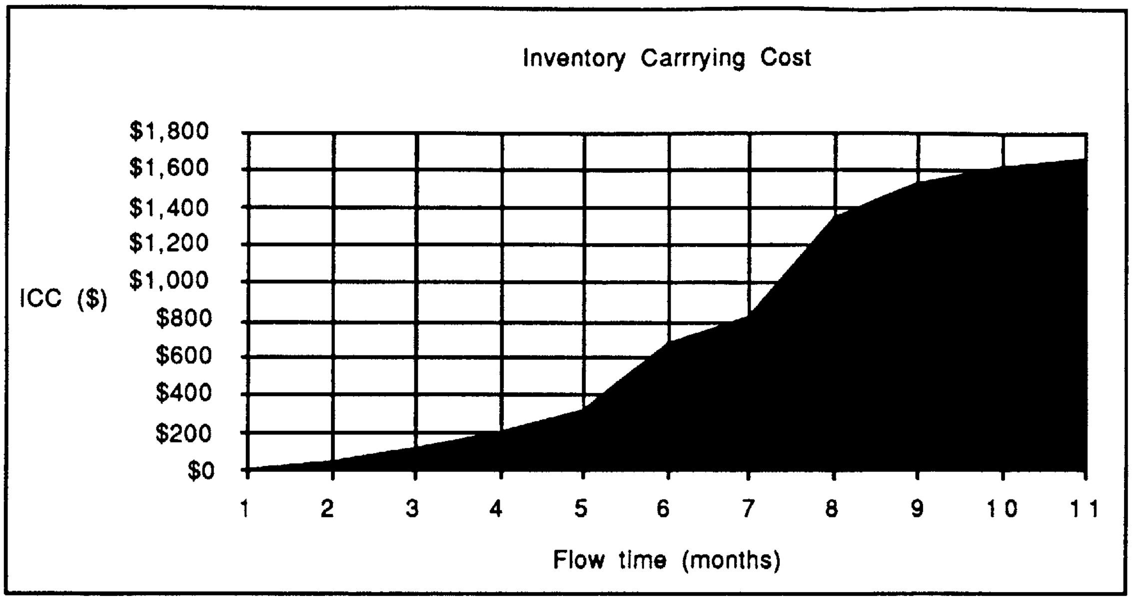

Figure 2: Inventory Carrying Cost ($/Airplane)

Revenue Opportunity Cost

In a market where there is immediate substantial demand for a company's product, there is a second element of cost associated with manufacturing flow time called revenue opportunity cost. Revenue opportunity cost is the potential revenue opportunity associated with collecting incoming sales revenue earlier if a shorter product flow time can be realized (deliver earlier). For example, in the airplane industry, demand for airplanes currently far exceeds supply. Boeing commercial airplane group currently has an $85 billion, four year order backlog[3]. An airline ordering a Boeing 747-400 today will not get delivery of the airplane until approximately 1997[4]. Given current

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[3] Boeing News.
[4] Boeing News.

market conditions[5], with airline passenger traffic predicted to grow at over 4% annually for the next decade[6], airline customers are eager to take delivery of newly designed, fuel efficient airplanes as quickly as possible. Given this market environment, there are 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. Imagine that a control code within the manufacturing process which presently has eight days of flow time (operating at a four day production rate) reduced 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, implemented in isolation, has simply created a one day buffer inventory at the particular control code. To realize the benefits of flow time reduction, the inventory buffer must be either "flow through" or "flow back" the manufacturing process.

By "flow through", we mean that the one day reduction is pushed through all the subsequent control codes in the manufacturing process. To accomplish this, all the control codes following the present control code must

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[5] This chapter was written prior to the 1991 Iraq-Kuwait crisis, which has had significant short term impact on airline operations and profitability due to increasing oil prices (up to 30% price increases in jet fuel prices) and decreasing passenger traffic (because of terrorist threats). The long term effects of the crisis on airline operations is not clear.

[6] Boeing News.

compress their schedule (by the amount of the flow time reduction) on the very first airplane when the flow through is to occur. Note that the compression for all subsequent control codes occurs only for the very first airplane during the flow through process. Thereafter, 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, all these control codes would simply experience a one day compression for the first airplane when the flow time reduction is flowed through; after that, the control codes should continue to operate as normal, one day ahead of the schedule it would be following under the previous, longer flow time.

Flow Through Illustration

To illustrate, let us look at Figure three below. Figure three is a sample production schedule for a hypothetical sequential job shop I have constructed to illustrate how flow time reductions can be flowed through the manufacturing process. From the figure, we see that the manufacturing process consists of three sequential control codes, control codes A, B, and C. We see that the manufacturing flow time for control codes A, B, and C are five days, four days, and five days, respectively. From the schedule, we learn that the production line is operating at a three day production rate (a product is completed every three days). 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. Assume that during a flow time reduction effort, the work team at control code A found a one day flow time buffer that it can reduce from its present flow time. How do we flow through this one day flow time reduction?

Table 1 below lists the start and completion dates for each of the control codes for all five jobs. Note that on job number four, where the flow time buffer is actually taken out of control code A and flow through the manufacturing process, 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 pre-accelerated start and completion dates for each control code under the previous, longer flow time). We see from both Figure 3 and Table 1 that after the one time schedule acceleration to flow through the flow time reduction, control codes B and C settle back to their regular production pace, starting and completing each job after the first flowed through job (job number four in the example) one day ahead of the old schedule. Note that this analysis applies similarly to a more complicated manufacturing process involving parallel flow of sequential manufacturing processes. The only difference occurs when the control code where flow time is reduced is positioned before the integration point (where the parallel processes converge). In this case, all parts in the parallel process flow that will be integrated into the first flowed through job will also need to have their schedules accelerated in order to synchronize arrival time at the process integration point.

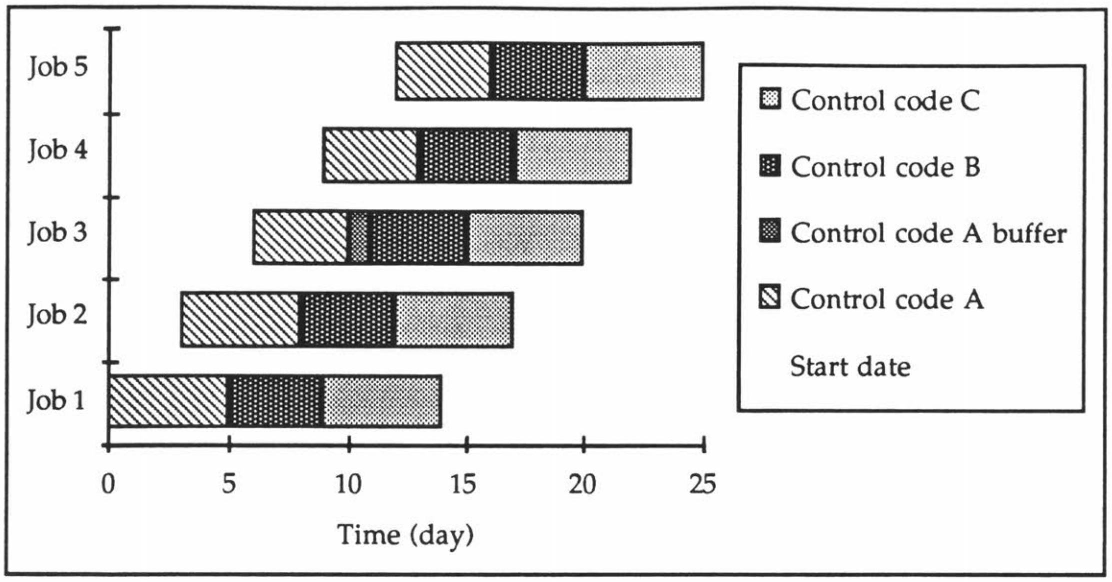

Figure 3: Production Schedule to Illustrate "Flow Through" Concept

	Control Code A		Control Code B		Control Code C	
	Start Date	Cmpletn Date	Start Date	Cmpletn Date	Start Date	Cmpletn Date
Job 1	0	4	5	8	9	13
Job 2	3	7	8	11	12	16
Job 3	6	10	11	14	15	19
Job 4	9	12 (13)	13 (14)	16 (17)	17 (18)	21 (22)
Job 5	12	15	16	19	20	24

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

Advantages and Disadvantages of Flow Through versus Flow Back

Instead of flow through, the company can choose to "flow back" the inventory buffer of the flow time reduction. That is, given the flow time reduction, all upstream control codes can start one day later than the old schedule and still be able to meet current delivery schedule. Since 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. However, since flow through shifts the production schedule ahead by the length of the flow time reduction, flow through achieves revenue opportunity cost savings as well as inventory carrying cost savings (for a manufacturing process involving parallel processes, revenue opportunity costs savings can only be achieved if the flow time reduction is for a control code on the critical path of the manufacturing process). On the other hand, flow back simply takes advantage of the flow time reduction by pushing back the starting date of the production schedule, thus helping the company only to reduce inventory carrying cost and not realize any revenue opportunity cost savings.

To summarize, a company can choose to either flow through or flow back flow time reductions. By choosing to flow through flow time reductions, a company will have to accelerate the production schedule for a pre-selected job in order to flow the flow time buffer through the manufacturing process. Once accomplished, all control codes (except the control code where the flow time reduction took place) in the manufacturing process will operate with the same flow time at the same production rate. The only noticeable difference will be that the production schedule will be shifted forward by the length of the flow time reduction that is flowed through the manufacturing process. By flowing through flow time reductions, a company will have to plan production carefully in order to account for the schedule compression for the first flowed through job. However, because flow through shifts the production forward by the length of the flow time reduction, flow through allows the company to realize revenue opportunity cost savings as well as inventory carrying cost reductions. Flow back, because it only involves delaying the starting date of every job after a designated flow back job, is very simple to implement. However, because flow back utilizes the flow time reduction by delaying the start dates, there are only inventory carrying cost savings and no revenue opportunity cost reductions. Put in other terms, a company can choose to implement the flow time reduction by either delivering earlier (flow through) or starting later (flow back).

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. Note that revenue opportunity cost (benefits) only exist on control codes which are on the critical path of the manufacturing sequence. That is, in order to improve the revenue opportunity element of flow time cost, the flow time for the *entire* product must be reduced and the income revenue stream brought forward (flow time reduction is flowed through the manufacturing process); thus, a reduction of the flow time for a control code that is not on the critical path of the manufacturing process does not reduce the product flow time and will not improve the revenue opportunity benefit of the product. Also, as previously noted, flow time reductions that are flowed back the manufacturing process will only bring about inventory carrying cost savings but not revenue opportunity benefits.

An example

Assume that manufacturing flow time for a much demanded product is ten months. Further assume that the product sells for $100 each and that the factory is operating at full capacity and has a two year order backlog. Thus, when a customer orders this product, the customer would not get delivery of the product for at least two years. Now, suppose that the company is considering a proposal to reduce its product flow time from ten months to nine months. What is the revenue opportunity benefit of this one month flow time reduction?

The revenue opportunity benefits[7] of the flow time reduction can be calculated as follows. If the company flows the flow time reduction through the manufacturing process, it would be able to ship product to each of its customers a month earlier. This flow time reduction will therefore, from a cash flow standpoint, enable the company to collect its $100 revenue from each of its customers a month 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.

Variable Tooling Cost

Variable tooling cost is especially important in Boeing's high capital, labor intensive manufacturing environment. This element of flow time cost is associated with the cost of purchasing and servicing required production tools

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[7] The one month flow time reduction will also bring about inventory carrying cost savings (see section on inventory carrying cost).

and equipment within the control codes in the manufacturing sequence. As noted previously, the number of job or tooling positions required in a control code is determined by the quotient of the control code flow time divided by the maximum cycle time (plus one if the remainder of the division is non-zero). For example, if control code 123 (a hypothetical control code) has eight days of flow time and is operating on a four day production cycle, the number of tooling positions (and in-process jobs) in the control code is equal to 8/4 = 2. If, on the other hand, the production rate needs to be increased to a three day production cycle (a completed job from each control code every three days instead of every four days), a new tool would have to be purchased and installed at the control code because the number of tooling positions required by control code 123 to meet the requirements of the new three day production environment is now (8/3 =2) +1 = 3 (we add one to the quotient because the remainder of the division is non-zero).

Now, suppose that the control code flow time can be reduced to six days (we will discuss near term and far term flow time reduction strategies later in this thesis), then the tooling requirement for the control code would remain at two (6/3 = 2) and the additional tooling position would no longer be needed. Therefore, we see that significant tooling cost reductions can be achieved through control code flow time reduction.

Calculating Variable Tooling Cost

Calculating variable tooling cost for a control code requires an estimate of the incremental tooling cost, the planned maximum production cycle rate for the airplane program, and the projected control code flow time based on the present production planning methodology. Note that variable tooling cost (and savings) occur in a step-wise manner (see Figure 4). This is because the incremental tooling cost being evaluated increases as steps (a function of the production cycle time). For instance, in the example above, a one day flow time reduction in control code 123 (bringing the control code flow time to seven days), is of no value within the variable tooling cost dimension[8] since a one day flow time reduction will not decrease the number of tools required at the control code (the number of tooling positions required at the control code is (7/3 = 2) + 1) = 3 positions.)

An example

To demonstrate a variable tooling cost calculation, we will use the control code above that is operating with eight days of flow time in a four cycle production cycle (a completed job every four days). Assume that because of market conditions, the factory wants to accelerate the production rate to a three day production cycle (a completed job every three days).

As we saw earlier, going from a four day production rate to a three day production rate will necessitate purchase and installation of a new tool since the number of tooling positions required by the control code will increase from 8/4 = 2 positions to 8/3 = 2 + 1= 3 positions. We will assume that the incremental tooling cost is $1.2 million dollars. What is the variable tooling cost (benefit) for flow time reduction at this control code?

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[8] The one day flow time reduction does bring about inventory carrying cost savings for the control code.

In this example, if we do not reduce manufacturing flow time at the control code, we will need to purchase a new tool for $1.2 million in order to produce at the faster three day production rate. If, however, we can reduce manufacturing flow time at the control code, we may be able to produce at the faster production rate without purchasing a new tool, thereby realizing significant variable tooling cost savings. To calculate the variable tooling cost (benefit) of flow time reduction, we note that a one day flow time reduction (bringing the control code flow time to seven days) will not reduce the need for the new tool since the number of tooling positions at the control code is still (7/3 = 2) + 1 = 3 positions. On the other hand, if we can reduce the flow time at the control code by two days (bringing the control code flow time to six days), we see that we no longer need to purchase the additional tool in order to produce at the faster production rate since the number of tooling position required now is 6/3 =2 positions (we already have two tools in the control code since we are presently operating with eight flow days in a four day production cycle, thus the number of tooling positions presently at the control code is 8/4 = 2 tools). Since a one day flow time reduction brings about no variable tooling benefit, but a two day flow time reduction brings about $1.2 million in variable tooling saving, we see that the variable tooling cost curve looks like a step function (see Figure 4).

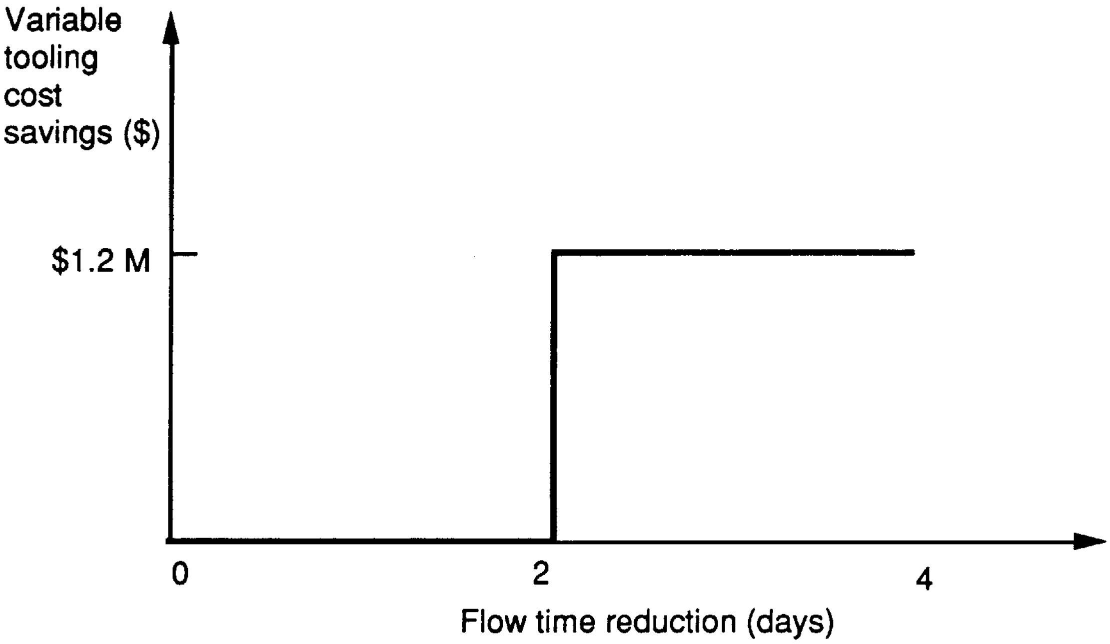

Figure 4: Variable Tooling Cost Curve

Flow Time Cost Integration

In the sections above, I have explained and derived each of the three major elements of flow time cost. Benefits of flow time reduction can be assessed by integrating these three elements together for the entire manufacturing process and noting the benefits of flow time reduction for each flow day. The integrated flow time cost is especially important when evaluating alternate production planning decisions involving trades of capital and/or labor investments for flow time (a detailed discussion on this methodology follows; see near term flow time reduction strategy). Note that flow time cost is best integrated by calculating in units of dollars per flow day per year ($/flow day- year) instead of dollars per flow day per airplane ($/flow day-airplane). Using the $/flow day-year unit (which gives the dollars saved per year for each flow day reduction) facilitates evaluation of flow time reduction proposals using the net present value (NPV) or pay back period methodologies.

Intangible Elements of Flow Time Cost

In addition to the three flow time cost components noted in the previous sections, there are intangible flow time 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, more corrective efforts are expended to resolve the production problems and rework all the parts that have built up in 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, because of its long manufacturing flow time, will require a longer period of time to bring in-demand products to market than competitors with short manufacturing flow times.

3.4 Implications of Flow Time Cost on Production Planning Methodology

What are the implications of flow time cost on present production planning methodology? What are the effects of flow time cost visibility on future production decisions? In this section, we examine the effects of flow time cost on present production planning methodology. Specifically, we examine the implications of flow time cost on alternate ways of utilizing productivity improvements.

Present Production Planning Methodology

At the start of a new airplane program, an initial number one airplane flow chart is constructed depicting the sequence and length of all manufacturing operations in the process flow based on product definition and on experiences from past airplane programs. The staffing level necessary to initiate and sustain production for each control code are then calculated based on estimated labor hours and planned manufacturing flow days. In a manufacturing environment where there is significant worker learning, the labor input per job needed by workers to complete required operations within each control code decreases as a function of the number of airplanes produced (see Figure 5).

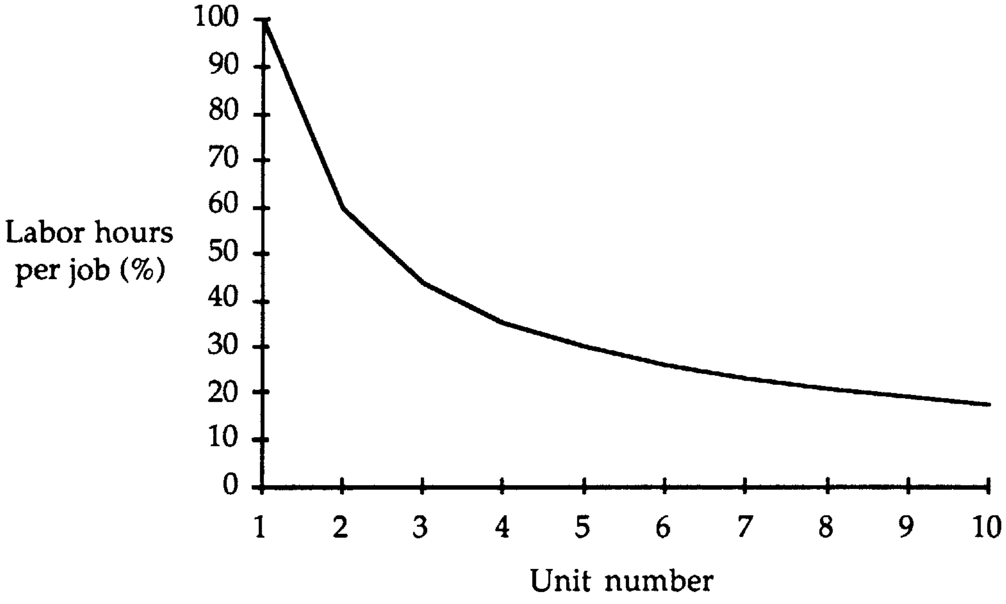

Figure 5: Sample Learning Curve

As the labor hours required by each control code in the number one flow chart decrease, the production planners have to decide how to utilize these productivity improvements. The improved labor productivity could be utilized by reducing the number of workers at the control codes, reducing control code flow time, or a combination of both. Currently, because of management emphasis on work force head count as the primary tool of cost control, and due to the lack of flow time cost visibility, production planners rely heavily on head count reduction as the primary means of realizing these productivity improvements, at the expense of flow time.

Proposed Production Planning Methodology

With visibility of flow time cost, I propose a new methodology for utilizing worker productivity improvements. Specifically, I propose that as labor hours required by each control code decrease because of worker learning, that these productivity improvements be realized through flow time reduction instead of work force reduction[9].

An Example

Assume that the first production unit of control code 856 (a hypothetical control code) is estimated to require 100 labor -days. To meet requirements of the 5 day production rate, the control code will initially operate with ten flow days and (10/5 =) 2 tooling positions. There will initially be (100 labor-days per job/5 day production cycle) = 20 workers working in the control code. Through worker learning, by unit 256, the labor content required to complete necessary operations will decrease to about 10 labor-days (however, because of manufacturing variances, labor content can range up to 16 labor-days per plane). Assume that because of projected market demand, the production cycle rate will be increased to a two day cycle. Table 2 lists three alternate 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 average labor content per job. Specifically, scenario one, the scenario with longest flow time, also has the lowest average labor input per job. To understand this, let us look at the scenarios in more detail. 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

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[9] Up to the limit dictated by minimum flow time and maximum crew size.

jobs) and smooth the work variability between incoming airplanes[10]. On the other hand, 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 (note that the labor content per job can range up to 16 labor-days per airplane). To meet the production schedule, the supervisor in scenario three has to staff the control code with (16 labor-days per job/2 day production cycle)= 8 workers (note that some of these eight workers may be idle when the work-in-process job requires less than 16 labor-days).

These scenarios illustrate the difficult choices facing supervisors and production planners on how they should utilize improved productivity. We see that by realizing productivity improvements through head count reduction, we maximize worker productivity (minimum labor content per job). However, we may also forgo significant savings in inventory carrying cost, revenue opportunity cost (if the control code is on the manufacturing critical path) and variable tooling cost. On the other hand, by realizing productivity improvements through flow time reductions, we bring about significant flow time cost savings but we also lose some of the productivity improvements. Under the present incentive system, which emphasizes schedule adherence and worker head count (but does not recognize flow time cost), production decisions are often made without considering flow time cost. This has in turn resulted in production decisions which, while minimizing labor content per job, do not maximize corporate profitability.

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[10] Please see "How increased flow times reduce effects of job work variations" in chapter 5 for detailed discussions.

Realizing Productivity Improvements through:

	Scenario 1	Scenario 2	Scenario 3
Flow Time	**10 days**	**6 days**	**2 days**
Cycle Rate	2 Days	2 Days	2 Days
Tooling Positions	**5** positions	**3** positions	**1** position
Staffing	**5** workers	**5-6** workers	**8** workers
Avg Input / Job	**10** labor days	**10-12** labor days	**16** labor days
Inventory Turns[11]	126/5 = **25.2**	126/3 = **42**	126/1 = **126**

Table 2: Three Different Ways to Realize Productivity Improvements

3.5 Near Term Flow Time Reduction Strategy

Given the discussions earlier on past production decisions that emphasized head count reduction at the expense of flow time and given the motivations toward flow time reduction, what can we do to reduce flow time? In this section, I introduce the near term flow time reduction element of the dual-prong strategy. Later in this thesis, I will introduce the far term flow time reduction element of the strategy.

Methodology

To bring about near term flow time reduction, I propose a two step process. First, I propose that the present flow time for all manufacturing control codes be evaluated against their minimum theoretical flow time. This evaluation would give an assessment of the opportunities available for flow time

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[11] Inventory turn of control code calculated as annual output divided by average inventory. Annual output calculated as 252/cycle rate = 252/2 = 126.

reduction. Next, I propose that specific trades of head count and/or capital investments for flow time reduction *within* each control code be evaluated on the basis of incremental cost (marginal labor efficiency loss and/or capital investment cost) and incremental benefits (flow time cost reduction through reductions in inventory carrying cost, revenue opportunity cost, and variable tooling cost).

For example, consider a control code, staffed with six workers (optimal crew size), which is presently operating with twenty days of flow time in a ten day production cycle[12] . Thus, labor input is (6 workers * 10 days * 8 hours per work day[13]) = 480 hours per job. The present operation minimizes labor input per job by operating at optimal crew size[14] while preserving manufacturing flow time to protect against unforeseen disruptions. Now, consider a proposal to reduce two days of manufacturing flow time at the control code by adding two more workers. Now, the labor input per job is (8 workers * 10 days * 8 hours per day) = 640 hours per job. The increase in labor hours per job is due to deviation from the optimal crew size (which reduces labor productivity) and worker idle time between jobs.

Using the present production planning methodology, the flow time reduction is a bad proposal since it increases the 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 control code is on the critical path of the manufacturing sequence, and the flow time reduction is flowed through the

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[12] Assuming eight hour, one shift-per day operation.

[13] Assuming eight hour, one shift-per day operation.

[14] See chapter two for detailed explanation of production planning methodology, including optimal crew size.

manufacturing process, the flow time reduction proposal would also bring about revenue opportunity cost savings.

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,the proposed production planning methodology, which places renewed focus on flow time reduction as the primary means of realizing productivity improvements, will bring about significantly shorter flow times for control codes in the manufacturing sequence as the number of airplanes manufactured increases. Therefore, as the product line gains market acceptance and approaches maximum production rate, the lower flow time of the new production planning methodology will translate to significantly lower facilities and tooling costs, in addition to substantially reduced inventory carrying cost and revenue opportunity cost. For a new airplane program, where capital investments add up to hundreds of millions of dollars and is not yet a sunk cost, the proposed production planning methodology can bring about significant program savings.

3.6 Conclusion

In this chapter, we reviewed flow time cost and the three primary cost elements of flow time cost. In addition, we discussed how lack of flow time cost visibility in the current management accounting system has resulted in production decisions that overemphasized head count reduction as the primary method for realizing productivity improvements, at the expense of manufacturing flow time. Given these motivations, we presented a near term flow time reduction strategy. Unlike the present production planning methodology, the proposed strategy focuses on flow time reduction as the primary method in realizing productivity improvements in the production line. We showed that with the new flow time reduction strategy, we realize the benefits of the labor productivity improvements and also significant flow time cost savings.

Chapter 4 ANALYSIS OF SYSTEM VARIANCE IMPACT ON DIRECT MANUFACTURING LABOR INPUT

4.1 Introduction

In this chapter, I analyze the impact of system variances on manufacturing labor input. Before proceeding to the analysis, let us define manufacturing variance. In this thesis, variances are defined as "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 my internship at Boeing, I learned first hand the impact of system variances on manufacturing productivity. Interviews with manufacturing supervisors, shop workers, and industrial engineers all indicate that significant portions of total manufacturing labor input are attributable to system variance-related activities. Mr. Deane Cruze, senior corporate vice president of Operations at Boeing, noted in his article, Breaking Out of the Box[1], that "We should be very concerned about our willingness to do many jobs over and over again. Why is it that we never have time to do it right the first time, but always have time to do it (rework) again?...We've done a lot of things right. Imagine what we could do if we just quit doing a few thing wrong."

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[1] Cruze, Deane. *Breaking out of the Box,* MANAGER - Boeing Management Magazine, Mar-April 1990.

In this chapter, I present a working hypothesis regarding the effects system variances have on manufacturing labor input and give definitions and descriptions of these manufacturing variances. I explain how statistical methods are used to test the validity of the working hypothesis and describe the actual procedures of the statistical regression analysis used for hypothesis testing. Finally, I present and analyze the results of these statistical regressions to determine the validity of the working hypothesis and to estimate the effects of system variances on manufacturing labor input.

4.2 Working Hypothesis

My working hypothesis regarding the effects of system variances on manufacturing labor input assumes that for each control code[2], there is an associated manufacturing baseline work package which the control code is required to complete as part of its function. Associated with this baseline work package is the baseline work time[3] which the control code workers need to complete the required tasks. The baseline work time (BWT) of a control code is a function of a number of factors including, among other things, the complexity of the work to be performed and the number of airplanes manufactured thus far [4]. Therefore, the complexity of the baseline work package plays a significant role in determining the initial time required to complete pre-assigned tasks (called the number one unit time) while the number of units manufactured and the slope of the learning curve play

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[2] Basic operational work units within Boeing final assembly operations. See Chapter 3 for definition and example of control code.

[3] In units of labor-hours per job.

[4] Learning curve effect. See chapter 5 for discussions on nature of learning curve.

significant roles in determining the actual baseline work time required by each control code to complete pre-assigned tasks for each airplane.

The working hypothesis assumes that the actual manufacturing time spent by a control code to perform the required tasks is different from (usually greater than) the BWT. This is because 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 part reworks which disrupt the process work flow and add extra work to the baseline work package. Therefore, these system variances change (usually increase) the labor input required by each control code to complete its operations (Figure 1).

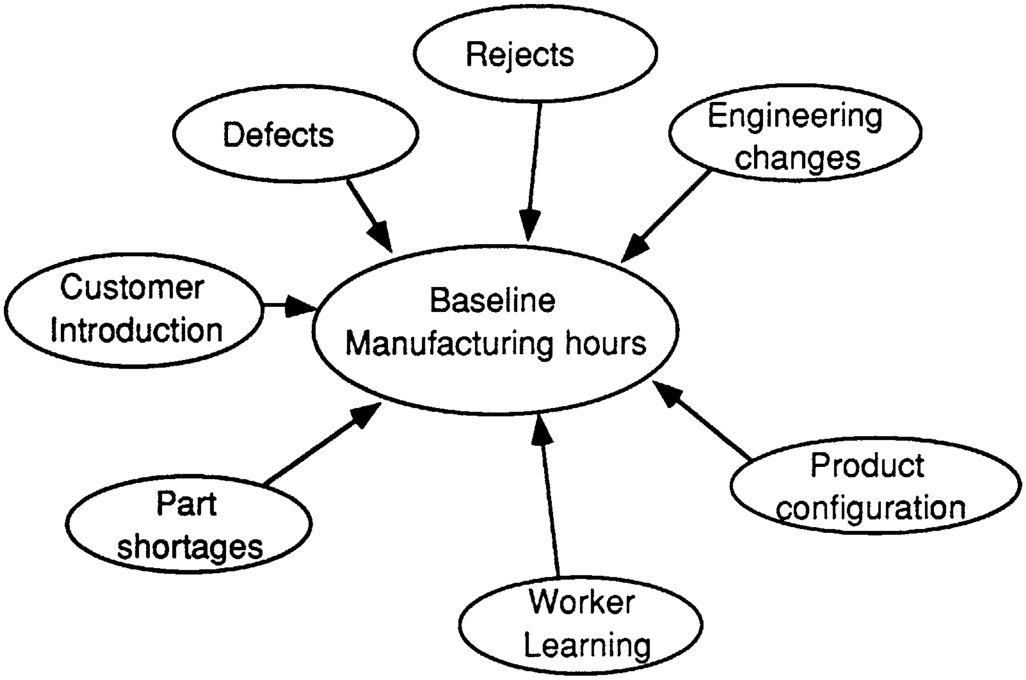

Figure 1: Working Hypothesis Illustration

I propose that the actual manufacturing time required to complete the baseline work package at each control code is equal to the sum of the BWT and the cumulative effects of the various external system variances. I test the validity of this working hypothesis by utilizing multivariate regression analysis to assess whether the manufacturing system variances have any statistically significant effects on the actual manufacturing labor input expended by the control codes to complete their baseline work packages.

4.3 Data Collection Methodology

To test the validity of the working hypothesis, I studied the Boeing 767 airplane program. In order to perform the multivariate regression analysis to test the working hypothesis, actual direct labor data and various system variance data were collected for most control codes in the manufacturing process for fifty consecutive Boeing 767 airplanes. Specifically, actual direct manufacturing major assembly labor hours (called Control Code 3 hours[5]) were collected for the manufacturing control codes in the 767 manufacturing sequence for fifty consecutive Boeing 767s. Similarly, data from over thirty different sources of manufacturing variances were compiled for the same fifty airplanes.

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[5] Note that this "control code" is a labor control code and is different from a manufacturing control code, which is an operational work unit in the manufacturing process.

Major Shops

During data collection, we uncovered a difference in the way that data for direct labor hours and data for the various system variances are kept. Specifically, we discovered that the direct labor hours, recorded by the manufacturing organization and collected by a group within the Finance department, is recorded and stored at the control code level. That is, the recorded hours expended by each control code for the manufacture of each of the fifty airplanes are available in the history files. On the other hand, the various system variance data, kept by a number of different organizations (such as Engineering, Manufacturing, Quality, and Industrial Engineering), are collected, aggregated, and reported by these organizations at what is called 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.

Because the manufacturing organization is structured along major shops, the variance data, which are collected and reported to the senior managers in charge of these shops, are aggregated together for all the manufacturing control codes contained in these major shops and are recorded and stored only at the major shop level. To insure compatibility of data, the actual labor data for all the control codes are aggregated by using the same method used by the Industrial Engineering organizations to aggregate the variance data for the major shops.

In addition, the data for the four major shops was aggregated to form a data set appropriate 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. Note that the actual labor input expended for manufacturing each airplane are collected for each control code for various labor hour control codes: cc3 (direct manufacturing hours), cc4 (rework hours), and cc5, cc6 and cc9[6] . However, because the data for labor control codes cc5, cc6, and cc9 are collected on an aggregate monthly basis rather than on a plane-by-plane basis, the analysis presented in this thesis will only consider the effects of variance impact on the direct manufacturing labor hours (cc3 hours).

4.4 System Variance Definitions

The definition and description of the system variances used in the statistical regression analysis are given below.

• *Blueline*	Bluelines are out-of-sequence work. That is, when work that is normally performed at a work station can not be completed there because of changes in the manufacturing plan, bluelines are generated for some other work stations in the assembly line to perform the uncompleted work. The bluelines in the regression are at the shop where the blueline work is actually performed.

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[6] Labor control codes for vendor rework, etc.

•*Greenline*	Greenlines are extended rejectable conditions. When a rejectable condition is found on an airplane, a rejection tag is generated to bring attention to the defect. If, it is determined, that the rejectable condition exists on other airplanes on the assembly line, greenlines are generated for these other airplanes so that rework can also be performed on these airplanes. Similar to the blueline, the greenline in this regression are the frequency count at the shop where the greenline work is actually performed.
•*PRR*	PRRs are production revision requests generated by the manufacturing or engineering organizations to revise the manufacturing plan of an airplane.
•*RR*	RRs (Rapid Revisions) are simple revisions to the manufacturing plan that is estimated to require no more than one hundred labor-hours to complete. Revisions requiring more than one hundred labor-hours are submitted as PRRs (which are subject to management review).
•*Rejection tag*	Tags written by the Quality Assurance department when parts or installations do not conform to standard and require corrective actions and/or signoff by Engineering. This variable is broken down into Engineering (rejection) tags and Operation (rejection) tags. Engineering tags are rejectable conditions attributable to engineering error

	while Operations tags are rejectable conditions attributable to Operations error
•*Defect*	Tags written by Quality Assurance when a part or installation does not meet drawing requirements. Defects are different from rejection tags because for a defect, corrective actions can be taken to make the part or installation meet drawing specifications. This rework can be accomplished without Engineering notification. Similar to the rejection tags, defects are also broken down into Engineering defects and Operations defects
•*Customer defect*	Tags written by the customer while the airplane is undergoing customer acceptance inspections. Similar to defects, repairs can be made to drawing specifications without Engineering notification.
•*Crew Rest (CR)*	This is an extra cost option available to airline customers for a closed-off section within the airplane where the airplane crew can sleep or relax.
•*New customer introduction (Class 1)*	Binary variable which denotes that a particular airplane is being delivered to a new airline customer. Usually, this signals Boeing that more time should be allocated to work with the airline in inspecting and accepting the airplane.

•*Customer introduction (Class 2, 3)*	Binary variables to denote different levels of customer deliveries to existing airline customers. Class 2 denotes existing airline customer, new airplane model (for instance, United Airlines, an existing customer of the 767-200, taking delivery of its first 767-300). Class 3 denotes existing airline customer taking delivery of a previously accepted model with minor modifications (for example, American Airlines (AA) taking delivery of its third 767-200, but this airplane is the first AA 767-200 with Pratt-Whitney engines instead of GE engines).
•*Log 2 of Unit number*	This variable is created to model the learning curve effect[7]. Value of variable is the log (base 2) of the unit number of the airplane (e.g. airplane 276 will have log 2 variable value of 8.109.)
•*Faster cycle*	This is a binary variable created to model a production rate increase that occurred within the airplane samples used in the regression. Airplanes produced under the slower rate have value of zero for this variable.
•*Faster cycle unit count*	This variable is created to model possible accelerated learning effects with the increased production rate. This variable has value of zero for airplanes produced under the slower production rate. For airplanes produced under the faster rate, the variable is assigned the value of the

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[7] See section on Log 2 of Unit number in this chapter.

	airplane's relative position in the faster rate (e.g. the first airplane produced at the faster rate has value of 1, the second airplane has value of 2, etc). The faster cycle and the faster cycle unit count variables are created to model the possible accelerated learning under the faster production rate.
•*SOS shortage*:	This variable denotes the number of occurrences where a part needed on the line is not available for installation. The frequency count is tracked at the shop where the shortages occurred.
•*Master Change (MC)*	Changes requested by the customer airline after the manufacturing plan for the airplane has already been completed. MC necessitates changes to the manufacturing plan and may require modifications to the airplane if the MC request is made after the airplane is already in production.
•*Change Request*	This is similar to the PRR. Change requests are specific requests for changes to the manufacturing plan that are generated by engineering after reviewing an MC.
•*Customer Airline AB*	This is a binary variable used to denote an airplane with engines that are not manufactured by GE or Pratt-Whitney (the two most popular engine manufacturers). This variable can also be used to identify airplanes delivered to Airline AB since it is the only airline in the sample that orders 767s with these engines.

• *Shop BFE rejection*	Buyer Furnished Equipment (BFE) are airplane equipment purchased by the airline customers to be installed on their airplane by Boeing. Examples of BFE include the galley, the seats, and the lavatory. Shop BFE rejection (used only at the J&I and Final Assembly shop since this is where all BFE are installed) denote the number of occurrence for each airplane when a BFE is rejected due to quality problems. The rejected BFE can then be reworked by Boeing or the BFE installation can be postponed until new BFE arrive.
• *Traveller*	As its name suggests, travellers are jobs that are not completed on time in the assigned control code that have to travel to a subsequent control code in the manufacturing process. Unlike bluelines, where the job is travelled due to changes in the manufacturing plan, travellers are jobs that have to be completed later because they were not completed within the allotted flow time (with no changes to the manufacturing plan). The four-digit number preceding the traveller variable indicate the shop where the travellers originated. The travellers in the regression indicate the number of travellers completed at each major shop (where the travelled tasks are actually completed).

4.5 Description of Regression Analysis

I conducted the regression analysis for the Boeing 767 on a statistical software package developed by Abacus Software[8] called StatView™. A total of five separate analyses were run for the Boeing 767 program. The first analysis, total airplane cc3 regression, is an analysis of variance impact on the entire 767 manufacturing process. The other four analyses are for assessing variance impact on each of the four major shops in the manufacturing process: Body structures, Wing structures, J&I (join and installation) and Final Assembly, and Field Operations.

Consulting Internal Experts

Before starting the regression analysis, I consulted with engineers and managers within Boeing's Industrial Engineering group to compile a list of relevant manufacturing variances which affect the production line. With this list, I worked with various organizations to collect and sort these data.

While running the regressions, I worked closely with my Boeing on-site advisor and the senior manager of Boeing's Industrial Engineering group at Everett to insure that the results of the analysis make sense and are consistent with their experience. Initially, I used a simple linear regression model, which incorporated all of the over thirty different system variance variables I collected for the 767 program as independent variables, and regressed all these variables against the dependent variable, cc3 hours. This

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[8] Abacus Software, Berkeley, California.

methodology did not work well as many of the different variables were often confusing each other in the regression, resulting in unsatisfactory solutions from the regressions.

From this experience, I concluded that before I started another round of regression analysis, I needed to understand what the critical system variances are that most impact manufacturing labor input. Knowing these critical variances, I can then begin the analysis by using these variances as the starting set of independent variables in the regression and then gradually refining and adding new variables to the starting set as necessary. So, to identify these critical variances, I conducted interviews with numerous industrial engineers, manufacturing managers, shop superintendents and factory managers to ask them what they thought were the top five variables most impacting the manufacturing labor input of the 767 program and each of its four major shops. The input from these individuals, who are the most experienced and knowledgeable people regarding the intricacies of the manufacturing process, gave me valuable insights about the manufacturing process. Their input also prioritized the list of variances which formed the starting set of variables for the new statistical analysis.

Stepwise Regression

To complement the new starting set of variables, I also began using a different regression model in StatView™ called stepwise regression[9]. Stepwise regression is a regression method which initiates each regression step by first

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[9] Stepwise regression is a feature contained within the StatView software package.

calculating the F-ratio for each of the independent variables. The model then selects the independent variable with the highest F-ratio[10] and includes this variable into the regression.

After incorporating the variable with the highest F-ratio into the regression and calculating the corresponding ANOVA[11] table, the model re-calculates the F-ratios for all the remaining independent variables against the regression residual. The model then selects the independent variable with the highest F-ratio above the user-selectable threshold for inclusion into the regression. Note that now the regression has incorporated two independent variables. After incorporating the two variables with the highest F-ratios, the model again calculate the ANOVA table and the root mean square (RMS) residual. Note that after including each new variable into the regression, the software re-calculates the coefficients and F-ratios of all the incorporated variables to minimize the root mean square (RMS) of the residual. If, after the incorporation of a new variable, an existing variable's F-ratio falls below the user-selected F-ratio threshold, the variable with the F-ratio below the threshold will then be removed from the regression.

Upon removing the previously included variable, the software re-calculates the coefficients, F-ratios, ANOVA table and RMS residual for all incorporated variables. As before, the model then calculates the F-ratio for all the remaining unincorporated independent variables. If there are variables with F-ratios above the user threshold, the variable with the highest F-ratio is then selected and incorporated into the regression. This selection,

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[10] The F-ratio, defined as $MS_{Treatment} / MS_{Error}$, is a measure which can be used to test the null hypothesis that all coefficients in the regression have the same value. Please refer to Engineering Statistics by Hogg and Ledolter for details.

[11] ANOVA stands for Analysis-of-variance.

incorporation, and re-calculation process will continue until all independent variables with F-ratios greater than the user-selectable threshold are incorporated into the regression model and all remaining unincorporated independent variables have F-ratios below the user-selected threshold. Using this methodology (with the user F-ratio set to 4.0), the stepwise regression model will only select those independent variables whose F-ratios are above the user-selected threshold. Using this model, along with the smaller starting independent variable set, the problem with all of over thirty independent variables confusing each other's effects in the linear regression model was addressed.

Assessing Surprising Results

This methodology worked well except for a few instances when the regression results defied reasonable expectations and experience (for example, rejection tags having a coefficient of -35 labor-hours per rejection tag; that is, rejection tags actually reduced manufacturing labor input!). In these instances, the cross correlation matrix of the independent variables incorporated into the regression was examined to determine if there were any significant correlations among these variables. If there were, I examined the origin of the correlated variables, and determined 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 was most appropriate to keep in the analysis, removed the other variable, and re-ran the regression.

A New Binary Variable

If I did not find a problem with the independent variables, I would also consult with the industrial engineering group to determine why the regression results were off. Through these consultation, significant insights were gained about the manufacturing process and the statistical regression model. In one case, we discovered that the problem with the regression resulted from a one-time only problem with an airline customer's malfunctioning airplane engine which significantly increased the labor hours expended for that particular airplane. However, because of the rarity of this type of incident, the incident was not tracked by any existing variables in the factory and thus was not reflected in any of the system variances in the regression.

Without proper account of the large deviation, the model tried to account for this deviation with existing system variance variables during the regression and significantly altered the sensitivity coefficients of all the variances in order to minimize RMS residual of the regression. In this particular case, after incorporating a new binary variable to account for the one time, extra-ordinary event, the software correctly attributed the deviation in labor-hours to the new variable during the regression and the coefficients of the other variables became reasonably consistent with experience.

4.6 Analysis and Discussion of Statistical Regression

The solutions of the five regression analysis for the Boeing 767 are shown below. The intercepts for each of these analyses were calculated as part of the regression (intercepts were not set to a fixed value). However, as each of these intercepts represents an estimate of the number one unit hour for the respective major shop, I am not including the intercepts in the variable tables below (because of the proprietary nature of the number one unit hour).

With respect to the regressions, we see that a large portion of the statistical variance in the major shop direct labor hours are accounted for (as indicated by the high adjusted R-squared parameter of the regressions) by some "vital few" manufacturing variances. Interestingly, the wing shop has a relatively low adjusted R-squared parameter because (I suspect) the analysis did not include work force skill and tool reliability indices (which are indices which measure the average aggregate years of experience of the work force and the uptime of the production tools, respectively) as independent variables in the regression. Unlike the other shops, customer-specific variances do not significantly affect the wing shop because wings are rarely modified for customer airlines. As a result, the work force skill and tool reliability indices should become very significant in the operation of the wing shop. Worker skills and tool reliability indices were not incorporated because neither of these indices were available by control code for the fifty airplanes. I am not terribly concerned, however, about not getting a better fit on the wing shop since the wing shop constitutes a very small portion of total labor hours utilized for 767 manufacturing.

Log 2 of Unit Number

To model the effects of the learning curve in the regression, I used a new parameter which I called "Log 2 of Unit number". This parameter is the logarithm (base two) of the cumulative production unit count. Classic learning curve assumes a log-log relationship between the unit labor hours and the cumulative production unit count:

log (unit labor hours) = x log (cumulative unit count) + log (constant) (Eq. 1)

where x, the slope of the learning curve, is the rate of worker learning (x ranges in value between 0.6 to 0.9, depending on the industry.)

The log-log worker learning model, however, does not work well for the statistical regressions used to analyze the effects of system variances on direct manufacturing labor input. This is because my working hypothesis assumes that

unit labor hours = a + bX + cY + ... + effect of worker learning (Eq. 2)

where a is the intercept of the regression, X and Y are frequency counts of manufacturing variances, and b and c their respective coefficients.

Now, if we use cumulative production unit count to model worker learning and we take the log of both sides of the above equation, we have

log (unit labor hours) = log (a + bX + cY+... + effects of worker learning) (Eq. 3)

As we see, taking the log of both sides of the unit labor hour equation changes the equation to a non-linear equation that is not conducive to regression. To simplify the regression, I decided to use the Log 2 of unit number parameter to model worker learning. This particular parameter is preferred over a simple cumulative production unit parameter because the cumulative unit number model assumes worker learning to be uniform for all production units. On the other hand, the Log 2 unit number parameter weighs worker learning much more heavily towards earlier production unit, thus more accurately modeling the nature of the worker learning.

Using the Log 2 of unit number parameter to model worker learning, the regression model becomes:

$$\textbf{unit labor hours} = a + bX + cY + \ldots + d^{*}\text{Log } 2\ (\text{unit number}) \qquad \textbf{(Eq. 4)}$$

Note that *d*, the coefficient of the Log 2 unit number parameter, can be interpreted as the change to the unit labor hours when cumulative production doubles. That is, whenever the cumulative production increases two-fold, the unit labor hours decrease by *d* hours. Thus, the Log 2 unit number parameter is quite different from the traditional learning curve model (which assumes that unit labor input goes down by *x*% rather than *d* hours when the cumulative production doubles).

Effect of Faster Production Rate

There was a production rate increase which took place during the manufacture of the fifty airplanes. To assess the relative impact of the faster production rate on the manufacturing labor input, I used two variables, faster production rate and faster production rate unit count, to model the effects of the accelerated production schedule. The faster production rate variable is a binary variable indicating whether a particular airplane was produced under the faster production rate. The faster production rate unit count variable is an integer variable indicating the relative unit count of the current airplane in the faster production cycle. For example, if airplane 256 is the fiftieth airplane produced under the faster production cycle, its faster production rate variable will have a value of one and its faster production rate unit count variable will have a value of fifty. On the other hand, airplane 125, which was produced under the slower production cycle, will have values of zero for both of the faster production rate variables.

I used two variables to model effects of the faster production cycle because in the regression analysis, we are really trying to assess two separate effects: the effects of worker learning for the entire manufacturing process and the effects of the faster production rate. I did not use a single logarithmic variable to model the effects of the faster production rate because the value of this logarithmic variable will be indeterminate for airplanes produced under the slower production rate.

Body Structures

The body structures shop is responsible for the assembly and integration of major sub-sections of the 767 fuselage. In this environment, where labor learning is significant, the shop is very sensitive to customer specific changes and associated disruptions. This is because customer airlines often request different interior specifications for their aircraft, which in turn affect the design and manufacture of different body sections and the associated manufacturing labor required to complete required tasks.

Variance and ANOVA Tables

R:	R-squared:	Adjusted R-squared:	RMS Residual:
.984	.968	.96	430.6

Variable	Coefficient (labor hour/occurrence)	Std. Err	F-ratio
Faster production rate	-1524.3	298.3	26.1
Faster production rate unit count	76.1	31.1	6.0
Master changes	379.9	95.3	15.9
PRR & RR	88.3	23.4	14.2
Engineering tags	83.6	19.8	17.7
Operation defects	0.34	0.17	3.8
Completed G/L	22.1	3.9	31.6
log2(x) of Unit number	-25168.7	5284.6	22.7

Discussion

The regression analysis for the body structures shop is unique in that the regression demonstrates the significance of the faster production rate. As indicated by the table above, the faster production rate had a beneficial effect on the manufacturing labor input required to complete pre-assigned tasks in the body structures shop. This might have come about because of the accelerated learning of the work force under the faster production rate (for a fixed amount of time, the work force is working on more airplanes, thereby increasing worker learning). However, as the positive coefficient of the faster production rate unit count showed, the beneficial effect of the faster production rate decreases as faster production rate unit count increases. This is because gradually, the difference between the regular learning and the accelerated learning, decreases as the unit count increases and the respective labor hours approach minimum value.

From the table, we see that Master Changes, Production Revision Requests (PRR) and Rapid Revisions (RR), Engineering rejections and completed Greenlines all have significant impact on the total labor input of the body structures shop. Interestingly, manufacturing labor time spent working on the completed Greenline and Engineering rejections are charged to a different labor code (cc4) from labor code cc3, which is the direct manufacturing hours used in the regression as the dependent variable. So, why do we see a sensitivity of cc3 hours to these two variables? One possible explanation is that these variables have secondary effects which affect direct manufacturing labor input.

Primary vs. Secondary Effects

A possible explanation for the non-zero coefficients for completed greenlines and engineering tags, which are suppose to be charged to a separate labor code, has to do with a new hypothesis regarding primary versus secondary effects of external system variances. I suggest that each variance (defined as factors or elements which affect the baseline work package) really has two associated effects on the actual manufacturing time required to complete required tasks.

First, there is the time required to actually perform the incremental work added on by the variance. So, in the case of a defect, where a rejectable but correctable condition is detected by the Quality Assurance department, the labor input required to actually correct the mistake is the primary component of the net effect of the defect on the total manufacturing labor input.

The variance, however, also has a secondary effect. This secondary effect of variances has to do with the impact of the disruptions caused by these variances on the work flow and the work force. For example, in the case of a greenline, where a rejectable condition detected on an earlier airplane in the production line is also present on the current airplane, the workers at the control code where the greenline is to be completed would first have to search for all specifically relevant paperwork instructing them on how to perform the rework. After that, they would have to plan the additional work around the existing work flow before they can actually perform the rework. All time spent on these non-value adding activities caused by the presence of the greenline is the result of secondary effects of variances. In this example, the effects of the disruption associated with the greenline, which interrupted the process work flow and disrupted worker learning, will have a significant impact on the direct manufacturing labor input required to complete the baseline work package. I call the effects of these associated disruptions of external system variances on the direct manufacturing labor input the secondary effects of variances.

Within the framework of the primary and secondary effects of variances on manufacturing labor input, it is therefore not surprising to see that greenlines and engineering rejections will still have an adverse effect on direct manufacturing labor input even after the actual labor expended to correct these conditions are charged to another labor control code.

Wing Structures

I did not get as high an adjusted R-squared parameter in the wing shop as I did with the other major shops. Unlike other shops, the wing shop, which is responsible for the assembly and integration of the airplane wings, is not very sensitive to customer variations. This is because wing designs are rarely altered for specific customer airlines.

Variance and ANOVA Tables

R:	R-squared:	Adjusted R-squared:	RMS Residual:
.747	.559	.496	442.635

Variable	Coefficient (labor hour/occurrence)	Std. Err	F-ratio
Customer A	813.5	274.6	8.8
Customer B	-1043.1	469.2	4.9
4-day unit count	-127.7	21.4	35.5
PRR & RR	436.5	105.8	17.0
log2(x) of Unit number	16516.4	3145.6	27.6

Discussion

Given the relative insulation of the wing shop from customer variations, the direct manufacturing labor input should be relatively insensitive to labor learning (the shop is already on the flat portion of the learning curve) and very sensitive to skills index and tool reliability. Unfortunately, I did not incorporate indices measuring relative labor experience and tool reliability[12]. Thus, I expect that once the skills index and tool reliability index are included in the regression, the adjusted R-squared of the regression should improve.

It is interesting to note that the log 2 of unit number parameter in the regression has a positive coefficient. This means that within the data sample, unit labor hours increased as cumulative production units increased. While this is counter to learning curve theory, I suggest that the positive coefficient of the learning curve parameter is due to two factors. First, as the rate of worker learning is high (because of the relatively few wing structure design changes), the wing shop is already operating on the flat portion of the learning curve. This makes the effects of the learning curve far less pronounced than in the other major shops. Second, I suggest that the positive coefficient of the learning curve parameter (log 2 of unit count) is possibly reflecting a relative decrease in the level of worker experience in the wing shop. As the shop is very sensitive to decreases in worker skill and experience (which increases the labor input required to complete pre-assigned tasks in the control codes within the shop) and these variables are not

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[12] These data are in fact available. However, the data are collected on a monthly basis by shop and are available only in that form.

reflected in any regression variables, the regression might have attributed relative decreases in the worker experience to the learning curve.

Join & Installations (J&I) and Final Assembly

The J&I and Final assembly shop is responsible for the join and integration of the major sub-sections of the airplane fuselage and for the installation, integration and testing of the major mechanical and electrical (including engines and avionics) sub-systems into the airplane. In this shop, where customer-to-customer variations significantly affect the tasks performed, system variances have a major impact on the direct manufacturing labor input of the J&I and final assembly shop.

Variance and ANOVA Tables

R:	R-squared:	Adjusted R-squared:	RMS Residual:
.984	.968	.955	478.44

Variable	Coefficient (labor hour/occurrence)	Std. Err	F-ratio
log2(x) of Unit number	-47132.1	3303.0	203.6
4610 Travellers	170.5	17.4	96.5
Engineering tags	7.8	5.2	7.2
Operations defects	3.4	0.32	112.7
Customer defects	3.0	0.84	12.6
BFE rejections	431.2	72.75	35.1
4650 Travellers	19.8	5.2	14.5
4625 Travellers	-56.9	7.2	63
Customer A	943.2	389.1	5.9

Discussion

Of the significant variables, we see that several travellers (three in all) have an impact on the direct labor input. While the positive coefficients for two of the travellers are as expected, the negative coefficient of the 4625 traveller is surprising. One possible explanation for the 4625 shop travellers' negative coefficient, which are travellers within the J&I and Final assembly shop (versus the other two travellers which are travellers to the Field operations shop), is that when the area supervisor sees that a job is about to travel to the next area within the J&I and Final assembly shop, he will likely send in the most experienced work crew to work on the traveller. The work crew, who are likely to work faster because of their superior experience and because the traveller is under intense time pressure to be completed, are likely to have a positive benefit on the total time required to complete the job.

We see that relative to the body structure shop, the sensitivity of the operations defects and engineering tags are significantly higher and lower, respectively. The defects in the J&I and final assembly area usually involve more rework than the defects in the body structures shop because J&I and Final assembly defects, since they occur later in the manufacturing process, typically require removal of some previously installed parts before corrective actions can be taken, thus taking more time. With respect to the engineering rejections, engineering rejections in J&I and Final assembly occur more frequently and involve smaller changes than the engineering rejections in the body structures shop. In the body structures shop, engineering rejections occur infrequently but have major impacts, thus the higher sensitivity of engineering rejections to direct labor input than the J&I and Final assembly shop[13].

Noteworthy in the table are the customer defects and airline customer A variables. The customer defects, which are defects detected by the customer airline that must be corrected, are usually perceived to be relatively cosmetic and part of the customer acceptance routine. Through the analysis, we see that the customer defects do have significant effects on the manufacturing labor input.

The airline customer A variable is noteworthy because while customer airline variables are usually not included in the regression analysis because effects of the individual airline customers are better reflected in direct impact manufacturing variables such as customer defects, operations rejections, etc, the airline variable was included in this regression to reflect a one-time, extraordinary circumstance involving problems with the customer airline's airplane engines, which caused the direct labor input to increase substantially[14]. Because the nature of this incident is not reflected in any of the regular system variance variables, I incorporated the airline variable to reflect the occurrence of the incident so that the statistical software can properly account for the otherwise unexplained increase of the manufacturing labor input related to the particular airplane.

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[13] Note that the effects for Engineering tags are secondary effects.

[14] See unique variance variables earlier in this chapter.

Field Operations

The field operations shop, which is responsible for flight test of the completed aircraft, is very sensitive to customer-to-customer variations. Specifically, as different customer airlines have very different acceptance procedures, the time required to complete customer acceptance of airplanes varies greatly. In addition, the field operations shop is also very sensitive to travellers from the J&I and Final assembly shop because these travellers can substantially alter the work flow of the baseline work package of the field operations shop.

Variance and ANOVA Tables

R:	R-squared:	Adjusted R-squared:	RMS Residual:
.838	.703	.678	1893.91

Variable	Coefficient (labor hour/occurrence)	Std. Err	F-ratio
Customer Airline AB	3998.9	1049.5	14.52
Late BFE	1878.8	824.7	5.2
4610 Traveller	98.6	28.1	12.3

Discussion

As expected, the table shows that Field operation labor input is particularly sensitive to incomplete jobs that travelled from the J&I and Final Assembly shop out to the Field. In particular, we see that travellers and late BFE (Buyer furnished equipment) variables are found to be significant. The late BFE variable (a frequency count variable) indicates that a buyer furnished component, which was scheduled to be installed in the J&I and final assembly shop, was late and had to be installed in the Field operations shop. We see that late BFE have significant impact on the manufacturing labor input at the field operations shop. The Customer Airline AB sensitivity reflects the additional time required to work with the customer airline to flight test the engines (non Pratt-Whitney or GE engines).

Total Airplane Regression

After performing the regressions for each of the major shops in the manufacturing process, I 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. Thus, this analysis gives a macro view of the significant variances for the entire airplane manufacturing process, not just the individual shops. 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.

Variance and ANOVA Tables

R:	R-squared:	Adjusted R-squared:	RMS residual:
.982	.964	.958	1696.072

Source	DF:	Sum Squares:	Mean Square:	F-ratio
Regression	6	2.55 E9	4.3 E8	147.7
Residual	33	9.49 E7	2.8 E6	
TOTAL	39	2.64 E9		

Variable	Coefficient (labor hour/occurrence)	Std. Err	F-ratio
Customer introduction	2964	769.7	14.8
Part Shortage	3.6	1.0	12.5
Production Revision Request	276.7	28.3	95.9
Model 200ER	-2247.8	878.4	6.5
Defects	1.3	0.46	7.47
log2(x) of Unit number	-47732.6	8117.8	34.6

Discussion

In this, the top-level airplane regression analysis, we see all the expected relevant variables in the regression: customer introduction, part shortage, production revision request, model 200ER, defect rework and log2 of unit number. The customer introduction variable, which indicates a new airline customer accepting the 767, usually requires quite a bit more direct manufacturing input because of the learning involving in assembling the first airplane for a specific customer airline to fit its custom specifications. 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.

The part shortage and production revision request variables have the expected effect of adding to the manufacturing effort required to assemble and test the airplanes. The baseline airplane model of the regression, because of its popularity and frequency of occurrence in the fifty plane sample, is the 767 model 300 (767-300). The model 300, which is approximately thirty feet longer than the model 200, requires more assembly and integration time than the model 200. As expected, the model 200ER variable has a negative coefficient, which indicates that the model 200ER airplanes require less time to manufacture. The defect variable, which counts the number of occurrences of correctable rejectable conditions on an airplane detected by the Quality Assurance department, is usually considered to be relatively insignificant in terms of its overall effect on total manufacturing hours. However, as we see through the analysis, defect rework labor significantly affects the total labor hours expended in the manufacturing of airplanes. Finally, as expected, we see a strong learning effect present for the total manufacturing labor input as a function of the number of airplanes produced.

Construction of Variance Pie Charts

With the variance table from the statistical analysis, we can construct a variance pie chart to assess the relative impact of manufacturing variances on direct labor hours. I will use a hypothetical example to illustrate construction of the variance pie chart.

Assume that a manufacturing firm analyzed the impact of manufacturing variances on direct manufacturing labor hours using the methodology detailed in this chapter. The variable table it got from an analysis of the manufacturing process (for one hundred production units) is

Variable	Coefficient (labor hour/occurrence)	Std. Err
Variable A	12.5	3.4
Variable B	3.6	1.0
Variable C	27	9.1
log 2 of unit number	-1452.6	350

To construct the variance pie chart, we need to have the frequency count of the relevant variables. The frequency count reflects the total number of occurrences for each manufacturing variance (during the production of the one hundred production units). Assume that we have the cumulative totals for each variable in the regression as follows:

Variable	Coefficient (labor hour/occurrence)	Frequency count (total number of occurrences)	Cumulative hours of variances
Variable A	12.5	1200	15000
Variable B	3.6	2000	7200
Variable C	27	300	8100
log 2 of unit number	-1452.6	n.a[15]	n.a

Assume that 200,000 labor hours were expended for the manufacture of the one hundred production units we are analyzing. Thus, the relative

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[15] Since the variance pie chart is used to illustrate the impact of manufacturing variances on total direct labor input, worker learning (as reflected by log 2 of unit number) is of little interest and is not applicable.

percentage of the individual contributions of relevant variables are as follows:

Variable	Coefficient (labor hour/occurrence)	Cumulative hours of variances	% of total manufacturing labor input[16]
Variable A	12.5	15000	7.5%
Variable B	3.6	7200	3.6%
Variable C	27	8100	4.05%
log 2 of unit number	-1452.6	n.a	n.a

From the table above, a variance pie chart can be now be constructed:

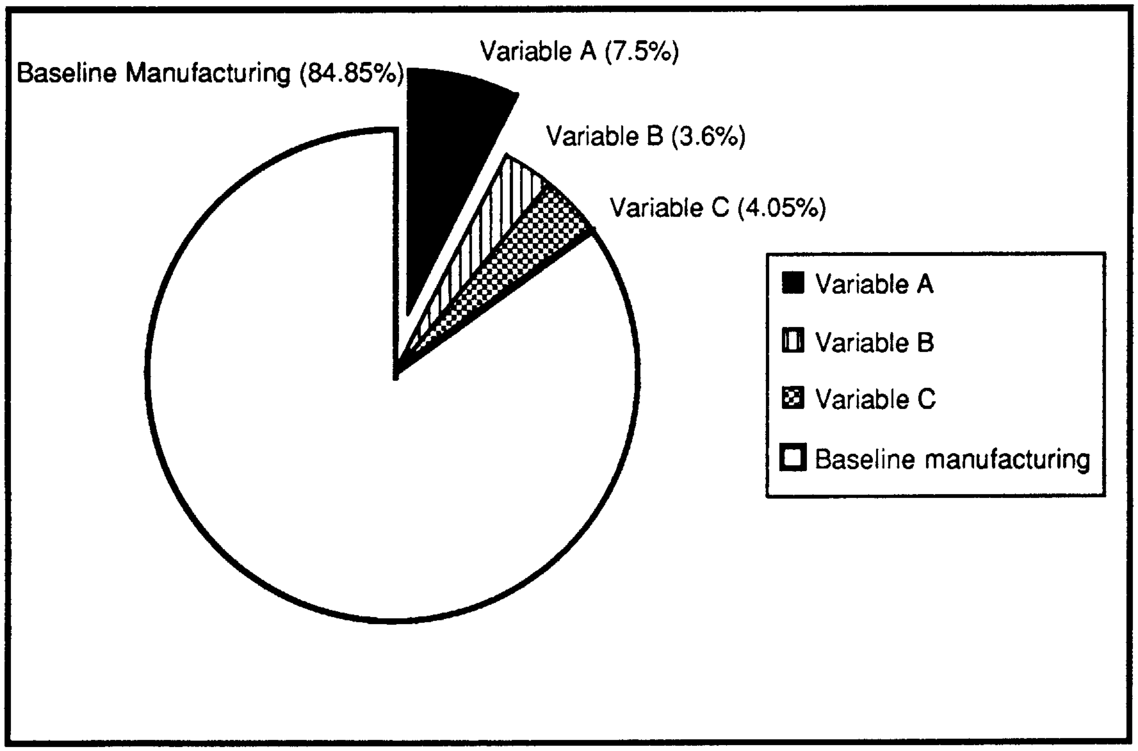

Figure 2: Variance Pie Chart

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[16] As a percentage of 200,000 labor-hours expended for one hundred production units.

Application of Variance Pie Charts

Using the methodology outlined above, variance pie charts were constructed for the four major shops and the entire airplane final assembly process of the Boeing 767 airplane. Because of the propriety nature of these data, the variance pie charts are not shown here.

Using the variance pie chart, a manufacturing firm can identify the high impact "vital few" variances that most affect the manufacturing process. Note that the most important manufacturing variances are not necessarily the variances with the highest sensitivity coefficients in the linear regressions. In fact, the most important manufacturing variances are those variances that made the largest contributions (in terms of cumulative percentages) to the variance pie chart. In the example above, note that even though variance C has a larger sensitivity coefficient than variance A (27 labor-hours/occurrence versus 12.5 labor-hours/occurrence), variance A has a larger impact on the variance pie chart than variance C (7.5% versus 4.05%).

4.7 Far Term Flow Time Reduction Strategy

In the previous section, I presented results of regression analysis showing that, consistent with Pareto principle, a few variances accounted 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 just knowing that certain variances affect the direct manufacturing labor input does not point to particular strategies for reducing the level of these variances.

In the regression analysis, one variance in particular, Operations defects, accounted for a significant portion of direct manufacturing labor input. Individually, each defect accounted for relatively few direct labor hours to correct; in aggregate, however, defects accounted for a large portion of the total manufacturing labor input for the 767 airplane program (based on relevant variance pie charts). In this section, I study the hypothesis that the engineering organization has an effect on the level of these defects and thus, plays an indirect role in determining the total direct labor input required to assemble the airplanes. I show that in particular, greenlines and engineering rejections (both variances directly attributable to Engineering) have significant impact on the level of defects and thus affect the amount of total manufacturing direct labor input required to manufacture airplanes.

Working Hypothesis

I suggest that because of the disruption effects of engineering changes and rejections, these variances have an indirect effect on the amount of direct labor input required to manufacture the airplanes. First, the engineering changes and rejections affect the total direct labor hour through secondary effects (as outline in section 4.5) where disruptions in the work flow increase the direct labor input required to completed pre-assigned tasks.

In addition, I suggest that the engineering changes and rejections affect direct labor input in another way. In particular, I suggest that the disruption effect of these variances, in addition to impacting direct labor input through primary and secondary effects, also adversely affect the direct labor input for an airplane by increasing the likelihood of worker error (i.e. defects). Specifically, I suggest that with the presence of engineering changes and rejections, which are conditions of variance that cause changes in the nature of the pre-assigned tasks in the control code, shop workers need to either consult with their supervisors or review new drawings to determine the proper actions to take for these variances. These disruptions, which affect the normal work flow of the assembly sequence, 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, I ran a regression analysis of defects as a function of numerous engineering variables. That is,

$$\text{Defect count (plane)} = a + b * (\text{Engineering rejections count}) + c * (\text{Greenlines}) + d * (\text{another Engineering variance}) + \ldots \tag{Eq.5}$$

where a is the intercept, and b, c, and d are the coefficients for the different Engineering variances. The result, presented in the table below, shows that defects are closely correlated to engineering rejections and completed greenlines. This relation between defects, engineering rejections and completed greenlines suggests an important strategy for productivity and flow time improvements in the manufacturing environment.

Variance and ANOVA Tables

R:	R-squared:	Adj. R-squared:	RMS Residual:
.868	.753	.74	509.6

Variable	Coefficient (defect per occurrence)	Std. Err	F-ratio
Engineering rejections	3.75	1.2	9.8
Completed greenlines	3.79	0.38	101.0

Long Term Productivity and Flow Time Improvement Strategy

Given the result of this analysis, which 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, suggests that by focusing Engineering efforts on reducing engineering rejections and greenlines, the level of defects can be decreased and labor productivity can be improved. Thus, by conducting cause-effect analysis on defects and by establishing significant correlation between defects and specific engineering release quality measures, we have established an interlink between Engineering and Operations.

With recognition of their respective impact on each other, Operations should be willing to invest in Engineering, in the form of human and/or capital investments, to secure Engineering commitment to improve specific measures in engineering release quality (such as engineering rejections and greenlines), which will in turn bring about reductions in defect levels that will result in significant improvements in labor productivity. 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. Thus, with proper recognition of the relative roles and impact of Engineering and Operations, a wise investment by operations can bring about significant variance reductions resulting in lower levels of direct manufacturing labor input required to perform pre-assigned tasks. The improved labor productivity can then be realized through flow time reductions, thus retaining the skills of the trained work force, decreasing the direct labor content of the airplanes, and reducing flow time cost.

4.8 Conclusion

As indicated by the high adjusted R-squared of the regressions for the major shops and the total airplane manufacturing process, the working hypothesis relating actual manufacturing labor input to baseline work time and the effects of external manufacturing variances is consistent with production experience. Given the results of the analyses for the major shops and the total airplane, along with the cause-effect analysis for defects, these analyses offer several lessons and suggest specific strategy for improving productivity and flow time. First, the regression focuses improvement efforts on the high impact variances instead of diverting attention onto all the variances. Second, the important variances are not necessarily the variances with the highest visibility. Instead, we should begin focusing our efforts on those variances which individually may not require much direct labor to correct, but, when aggregated, account for significant portions of the total direct labor input (such as defects). Third, Engineering has an important indirect impact on direct manufacturing hours through the effects that engineering release quality has on high impact variances such as defects.

Taken together, these lessons suggest a concrete long term flow time reduction strategy. Specifically, by investing in Engineering, with commitments to improve engineering release quality by reducing associated engineering changes and rejections, Operations can dramatically improve its productivity (through reduced variance-related activities due to improved engineering release quality) and profitability by realizing these productivity improvements through flow time reductions which brings about lower direct labor input, decreased variable overhead, and most importantly, flow time cost savings.

Chapter 5 ROLE OF INCENTIVE SYSTEMS IN MOTIVATING ORGANIZATIONAL CHANGE

5.1 Introduction

This chapter examines the role of incentive systems in motivating and sustaining organizational change. We begin by first reviewing the current incentive system and analyzing how the present system affects the behavior of individual organizations. We see that with the present production planning system, where productivity improvements are primarily realized through labor reductions, there is a negative feedback to line workers to improve process efficiency due to fears for their job security. I suggest that incorporating flow time as a specific performance objective will better focus management's attention on *total product cost* (which includes flow time cost), compared to the present situation, where management attention is focused primarily on the labor and capital equipment components of total product cost.

Specifically, I propose that flow time cost responsibilities be moved down from the corporate level to the operating division level to properly recognize the central role that operating divisions play in determining corporate flow time cost. Under the proposed system, where flow time cost responsibility is pushed down to the operating division level, long term corporate profitability objectives are better served since division management will be in a far better position to make appropriate production and resource allocation decisions based on the new, total product cost concept rather than under the present system, where division management are making production and resource allocation decisions primarily focused upon managing labor cost and capital expenditures. The proposed system empowers the operating divisions, who are in a far better position to be able to understand and assess the relative effectiveness and associated costs and benefits of specific flow time reduction proposals than the corporate office, to evaluate and implement those proposals that most benefit divisional and corporate profitability goals.

5.2 Current Incentive System

Presently, operating division general managers judge the relative performance of their divisions during the fiscal year by determining whether the divisions have met their delivery schedules within allotted budgets. At the operating division level, operating budget consists of, among other things, capital expenditures and head count. As a result, divisional head count and capital expenditures are closely monitored by management. In this section, I examine the effects that the current incentive system have on head count management policy and capital expenditure decisions.

Head Count Management

Under the present system, operations managers are given head count targets for each quarter. These head count targets are negotiated ahead of time between the Operations and Finance organizations during the annual division budgeting process. These head count targets are based on production and labor variables such as production rate, worker skill index[1], and learning curve. The learning curve assumes that the number of labor hours required to manufacture a product decreases as a function of the quantity of the product produced. According to learning curve theory, unit labor hours decrease because workers learn about specific aspects of the manufacturing process for the particular product as they become more experienced.

Relation Between Learning Curve and Worker Skill Index

Learning curve benefits are in addition to skill index benefits because skill index focuses on the general experience level of the work force while learning curve focuses on the specific learning that workers gain about a particular manufacturing process. Although separate, skill index and learning curve are not necessarily independent and might affect each other as follows. An experienced work force (with correspondingly high skill index) should lower the number one unit hours required to manufacture the first unit airplane. In addition, the slope of the learning curve (rate of worker learning) might also be a function of the worker skill index since the more experienced workers should learn faster than a less experienced work force. Thus, skill index and learning curve are two separate but not necessarily independent parameters affecting the total labor hours required to manufacture airplanes on the production line.

In the present methodology, as the number of airplanes produced increases, the number of labor hours allotted to manufacture each airplane is

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[1] This index is a measure of the aggregate work experience of the labor force.

reduced based on historical learning curve rates calculated from past airplane programs. Under these situations, managers are judged on whether they can meet production goals within the allotted head count without utilizing significant amounts of overtime to buffer against unforeseen variances.

How Incentive Systems Affect Flow Time Buffer and Head Count

In the current incentive system, management relies heavily upon head count reductions as tangible proof of productivity improvements on the shop floors. As a result, operations managers control head count targets closely and rarely deviate from these targets. Hayes, Wheelwright and Clark[2] (among many others) noted, "you get more of what you inspect, not what you expect." Thus, Operations managers, motivated by the incentive system to meet production schedule within a given head count goal without utilizing too much overtime, learn to use flow time and inventory buffers to insure that they meet these objectives.

As noted in section 3.3, without visibility of flow time cost, Operations managers may increase their production flow time to insure that they meet production schedule within given head count target since longer flow time gives them the flexibility to better manage varying work loads between consecutive airplanes. For example, if a control code has four days of flow time and operates in a four day production cycle, there is only one tool in the control code and the control code works on one job at a time. In this case, if the job content of each airplane varied greatly (because of manufacturing

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[2] Hayes, Wheelwright, Clark. Dynamic Manufacturing, 1988.

system variances), the demand on the work force will vary significantly from airplane to airplane.

Thus, in this instance, to insure that the control code always meet production schedule, the control code must be staffed at a level such that it is able to complete even the most labor intensive jobs within the allotted manufacturing flow time. This method, while insuring that production schedules are met, means that some workers will remain idle during jobs where the labor input required is less than the capacity of the staffing level[3] . Because of the varying nature of the work load, head count targets based on the expected average of job work loads could not be met by the control code supervisor without incurring schedule risk. Under the present system, this practice leads to unfavorable management reviews since the control code supervisor will be hard pressed to meet schedule needs within target head count.

How Increased Flow Times Reduce Effects of Job Work Variations

Now, if this same control code has six days of flow time (compared to four flow days in the previous example) and still operates in the four day production cycle, there will be two tools in the control code operating simultaneously on two consecutive jobs. The control code supervisor has some flexibility to better utilize his work force by shifting workers from one job to another. The greater number of jobs in the control code has a smoothing effect on the labor requirement at the control code because if a

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[3] In this example, the control code is staffed to be able to complete even the most labor intensive jobs within the allotted flow time.

difficult, labor intensive job is followed by a relatively easy, low labor requirement job, the supervisor can move people from the easy job to the hard job and hence balance the work load between these work teams within the six days allowed per job.

Thus, the longer manufacturing flow time, resulting in the larger number of jobs in the control code, has a "rolling averaging" smoothing effect on the work load in the control code. With longer flow times, control code supervisors can staff at a level closer to the average of the work load than he can under the shorter flow time. So, the increase in the flow time (which we term a flow time buffer) gives control code supervisors the flexibility to move workers around to maximize worker productivity and better adhere to head count targets. Given the incentive system's emphasis on head count and schedule, we should not be surprised to discover that operation supervisors are motivated to maintain longer flow times or flow time buffers.

Cost of Flow Time Buffers

While the benefits of flow time buffers are attractive, the cost associated with these flow time buffers are considerable. Increased inventory carrying cost, revenue opportunity cost and variable capital cost are only the more tangible costs of these buffers. These flow time buffers also have many intangible costs[4]. The flow time buffers increase the length of time required to get feedback on production problems from the line, thus increasing the amount of rework performed since corrective actions are longer in coming. The flow

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[4] See chapter 4 for discussion of intangible costs of flow time.

time buffers and associated inventory also cover up production problems and impede Total Quality Management (TQM) teams' efforts. These are only some of the many intangible costs of flow time buffers and must be taken into consideration when weighing the relative costs and benefits of flow time buffers.

Negative Feedback to Workers

As discussed in the earlier section, one of the shortcomings of the current system, where the line managers in the factory manage the line to adhere to head count targets, is that these managers are forced to increase flow time in order to meet production schedule within head count targets, thus incurring numerous tangible and intangible flow time costs.

Another shortcoming of the present system, which overemphasizes head count as the primary cost control method, is the negative feedback to line workers to improve product quality and labor productivity. Since head count targets are based on learning curve slope (the rate of worker learning), the faster the work force learns, the faster the work force head count decreases. Under such conditions, the work force is really being asked by management to sacrifice its own self interest by sharing insights learned about the manufacturing process. By improving quality and productivity which increases worker learning over and above the learning curve, the workers are further jeopardizing their own job security. Thus, if the workers learn any productivity improvement processes, they are likely to keep the knowledge to themselves because of the negative feedback in the present head count driven production planning system.

Effect of Present System on Capital Expenditures

In the present system, capital equipment expenditures are primarily driven by technological requirements of the production environment (automated riveting systems for improved reliability and repeatability). Occasionally, capital equipment expenditures are justified on the basis of production cost savings. In these instances, the capital equipment are usually automation equipment justified on the basis of cost savings related to reduced number of line workers. Thus, capital expenditures relating to quality or reliability improvement projects which have benefits that are hard to quantify are difficult to justify under the present system.

Effect of New Incentive System on Capital Expenditures

Under the proposed system, where flow time cost is visible and its reduction a specific management objective, capital expenditure requests dealing with improved product quality and tool reliability that were not approved in the past because of lack of financial justification now have a better chance of being approved. This is because proposals dealing with improved product quality and tool reliability helps to reduce manufacturing system variance. As discussed in chapter 4, lower variances lead to improved labor productivity which can in turn translate into flow time reductions which bring about significant flow time cost savings. Thus, if a capital expenditure proposal dealing with product quality or tool reliability can bring about improvements in the "vital few" manufacturing variances or better yet, directly lead to flow time reductions, the proposal will now have established tangible benefits (reduced flow time cost) for its implementation. Thus, the incorporation of flow time cost into the management incentive system will increase the likelihood for implementation of these important, but formerly overlooked, projects.

5.3 Incentive System Recommendations

To address the issues raised in the previous sections, I suggest that the current management incentive system be analyzed and restructured as necessary to properly align worker interests and management objectives with corporate goals. Specifically, I propose that, as a first step, flow time cost be charged to the operating division's annual budget, thereby moving responsibility of these costs from the corporate level to the operational level where the costs are actually incurred. There are several advantages to this re-alignment.

First, by charging flow time cost to the Division operating budget, this should encourage cross functional communications during the budgeting process between the Engineering and the Operations organizations. By having a common objective, that is, lowering total product cost (which includes flow time cost), it will be in the common interest of both organizations to increase inter-group communications. Through the increased communications, these groups will better understand the relationship between Operations and Engineering and recognize how one organization's actions affect the other organization's well being.

Presently, the Engineering and Operations organizations have separate and distinct functional responsibilities, each organization pursuing similar but sometimes diverging objectives. The Engineering organization, while recognizing that design for manufacturing (DFM) is important, is still primarily judged by management on whether or not it has met project design schedules. The manufacturing organization, which has relatively little influence on the Engineering organization, is judged by management on adherence to schedule and labor cost rather than schedule and total production cost. As a result, these organizations operate relatively autonomously and there are little interactions between these groups and little recognition (officially) of the relative impact these groups have on each other.

New Cooperative Efforts

With the proposed change of incorporating flow time cost into the management budget, I hope to encourage Operations and Engineering management to recognize their respective roles and impact on each others' organization and initiate new joint efforts to bring about lower flow time costs which benefits both organizations. It is important, under this system, for Operations and Engineering to recognize that improved engineering releases reduce important manufacturing variances such as defects[5], engineering changes, and part shortages, and, that lowering these variances can in turn brings about significant reductions in direct labor input required for the manufacturing of the airplanes. More importantly, it is critical that

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[5] See chapter 4 for discussion of relationship between defects and Engineering rejections.

these two organizations realize that reductions in manufacturing variances will not only decrease direct labor, but also decrease variable overhead and manufacturing flow time costs.

Relation Between Direct Labor Input and Flow Time

The reduction in variances enables manufacturing to reduce flow time because currently, a significant portion of direct labor input is attributable to variance-related activities[6]. The direct labor input is in turn related to flow time since direct labor input per job at a control code is equal to flow time (in work days) multiplied by the number of workers in the control code working on the particular job[7] (not necessarily equal to the total number of workers in the control code since the control code may have more than one job or tool position[8]). Thus, since a portion of the direct manufacturing labor input is allocated for variance-related activities, by noting the relationship between direct labor input and flow time, we see that a portion of the present manufacturing flow time is similarly allocated to expected variance-related activities. So, if the level of significant manufacturing variances are reduced, the portion of present flow time that is currently allocated for variance-related activities can then be reduced without increasing risk to the production schedule.

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[6] See chapter 4 for discussion on relationship between variance and flow time.

[7] Multiply by eight hours per work day.

[8] Direct labor input per job can also be calculated using the following formula:
Direct labor input = (production cycle time) * (total number of workers in control code).

Mutually Beneficial Actions

From the earlier section, we see that improved engineering releases impact operations by reducing the level of the external variances affecting direct labor hours. This in turn reduces direct labor cost, variable overhead and lowers flow time cost by reducing the flow time buffers previously allocated to variance-related activities. Under the proposed incentive realignment, I hope that the new common objective of reducing flow time cost (the first step toward the eventual goal of recognizing total product cost) will encourage and enable the Operations organization to "invest" in Engineering, with either human and/or capital investments, to improve the quality of engineering releases which will in turn improve their own productivity and increase the profitability of the entire division. To do this will require recognition of the two organizations' relative impact on each other and require close coordination and team effort between the groups and encourage team efforts between these two organizations.

Shop Floor Implementation

To motivate continuous flow time improvement at the shop floor level, I propose that flow time be added to the manufacturing performance objective for control code supervisors and that flow time savings be shared with responsible work teams. Specifically, I suggest that flow time cost be charged to the control code budgets. I suggest that when a control code supervisor wants to add flow time, he[9] will be charged the respective flow time cost to his budget. Similarly, when a control code supervisor reduces flow time in the control code, he will be credited with the flow time cost savings (the savings should be credited to the budget annually since the flow time cost savings is of a recurring nature relative to the old flow time cost structure).

Note that this proposal makes no assumptions about how much buffer is in the present flow time and does not penalize supervisors if they are unable to (or do not wish to) reduce flow time. However, if a control code supervisor wants to add flow time to his control code, this proposal forces him to carefully evaluate all other alternatives before adding the flow time. This insures that flow time is not further buffered simply because it is the easiest thing to do.

On the other hand, if a control code supervisor is innovative and works closely with his work team and the Industrial and Manufacturing Engineering groups to improve productivity and reduce flow time buffers, they will be recognized and rewarded jointly for their efforts. This proposal encourages the control code supervisors, their respective work teams, and the Industrial and Manufacturing Engineering groups, people who have the best knowledge about the specific tasks in the control codes and the actual time required to execute them, to weigh the relative costs and benefits of flow time reduction consistent with corporate profitability objectives. That is, unlike the present system, where management focuses primarily on head count and capital expenditures, the proposed system will encourage the work teams to

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[9] For readability, I will use the male gender form to refer to control code supervisors instead of he/she for the remainder of the chapter.

look at reducing the overall product cost as opposed to simply minimizing the labor and capital expenditure component of total product cost.

Work Team Implementation

Presently, there are few shop floor work teams at Boeing. Past efforts to implement work teams in the work place have met with limited enthusiasm or success. I suggest that these implementation efforts have been hampered (at least partly) by the hierarchical structure of the organization and by the lack of incentive system adjustments to motivate the manufacturing organization toward work team structure[10].

The team structure, while encouraging team work and group problem solving, also requires that team members freely share knowledge and information with each other. The team concept thus has many implications for the power structure of the work place. First, by having work teams that can take the initiative to identify and solve production problems on their own, supervisors and managers effectively lose some degree of control (and power) over the activities of the work teams. Second, to effectively implement the work team structure, team members must pool together their collective experience and resources to solve the problem at hand. While sound in theory, when put in practice, the team concept requires the effective surrender of the key determinants of relative prestige and power among shop workers: knowledge and information. Thus, the team structure requires

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[10] Lack of union support may have also hampered past work team implementations.

senior workers to, in effect, give up a portion of their source of power for the common good of the team.

Unfortunately, this practice is not encouraged by the current incentive system. In a work team environment, where the most senior and knowledgeable workers have the most to lose with respect to their power and influence, these workers are not currently motivated by the incentive system to contribute to their work teams[11]. It is therefore not surprising that the most experienced workers in the production line are usually unenthusiastic about work team implementations in their area. I suggest that this lack of enthusiasm has less to do with the "old timer" attitude often cited as the reason for these workers' attitude as much as these workers' recognition of the relative power shift associated with the work team structure.

To encourage work team implementation, I suggest that team performance be included as a key measure in an individual worker's performance evaluation. Furthermore, I propose that workers be recognized and rewarded on the basis of their willingness to help and assist others members of the team and their relative contribution to the team's overall success. This realignment (implemented through supervisors and peer reviews) thus addresses some of the concerns noted above for the most experienced shop workers. With the new structure, experienced workers will not be rewarded by what they know, but rather, by how they contribute their know-how toward the success of the team. By judging the workers' performance by their relative contribution to the team's success, it will be to the advantage of experienced workers to work and contribute within the team

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[11] Under the current incentive system, a worker's pay is solely based on his/her job classification and associated skills.

to improve their relative importance and influence (both of which should be rewarded with proper recognition and compensation).

With respect to the supervisors and managers who stand to lose some degree of control over the activities of the work teams, I propose a similar reward system which judges the performance of these managers by the relative performance and learning (skills improvement of work team members) of their work teams. This realignment should hopefully motivate supervisors and managers to overcome their initial reluctance and begin emphasizing the advantages of the work team structure (and the skills set improvement of individual work team members). Without the cooperation of these supervisors and managers, work team implementations have little chance of success.

Thus, while incentive systems alone do not explain the lack of success of work team implementations at Boeing, I suggest that realignment of the incentive system is a minimum necessary condition that should significantly impact the future success of work teams at Boeing[12].

Precautions

Associated with these proposals, however, are possible complications that should be taken into account prior to implementation. In particular, in the proposals to motivate control code work teams to reduce manufacturing flow

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[12] For more information and background on the benefits of work teams, please refer to a joint thesis study conducted at the Digital Equipment Corporation (DEC) which showed that work team implementation (using Just-In-Time inventory control policy, Statistical Process Control (SPC) and cross training) strongly correlated to improvements in product quality, team productivity and process efficiency. See Camhi and Tai theses, MIT, 1991.

time, proper precautions must be taken to insure that these flow time reduction efforts do not adversely affect product quality.

5.4 Organizational Implications of Recommendations

As previously noted, the proposed changes in the management incentive structure can bring about desired inter-organizational communications between Engineering and Operations. However, success of these changes are not guaranteed. Clearly, simple incentive system changes alone will not necessarily bring about desired organizational changes within the organization. Under the current leadership, the company has stressed the importance of total product quality and the importance of team work (between workers and management and between Engineering and Operations). I have suggested a possible scenario where, by aligning the objectives of the Engineering and Operations organizations more closely (by incorporating flow time cost into the management report card), these two organizations can better understand and recognize their respective roles and impact on each others' actions and promote new team efforts to brings about productivity improvements resulting in total product cost reductions (which benefit both organizations).

5.5 Conclusion

In this chapter, I presented some recommendations on how Boeing can better align its incentive system to motivate its work force towards continuous flow time improvement. In addition, I suggested specific shop floor implementation proposals to encourage flow time reduction initiatives at the manufacturing shop floor. Contained within all these proposals is the aim to start evaluating the performance of the operating divisions using the same criteria which the company uses to judge its own performance. Thus, the operating divisions must begin to recognize and take responsibility for total product cost, not simply certain specific components of the total cost that can result in sub-optimization of production decisions which adversely affect corporate profitability.

CHAPTER 6 CONCLUSION

6.1 Introduction

In this chapter, I review recommendations made in this thesis and describe actions taken by Boeing to address these recommendations. I also discuss how the methodologies presented in this thesis can be applied to other manufacturing industries.

6.2 Summary of Recommendations

The following is a summary of the three recommendations I presented to senior Boeing management.

I. Recognize flow time cost[1]

Presently, Boeing's management accounting system does not incorporate flow time cost[2]. I show that there are three major cost elements associated with manufacturing flow time: 1) inventory carrying cost, 2) revenue opportunity cost, and 3) variable tooling cost. I suggest that inclusion of flow time cost in the management performance evaluation system (at all levels) will refocus present production planning methodology on the reduction of total product cost (including flow time cost) instead of its present emphasis on reduction of labor cost.

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[1] Please see chapter three for detailed discussions.

[2] See chapter three for detailed discussions of flow time cost.

II. Implement flow time reduction strategy[3]

With motivation to reduce flow time, I propose a concurrent dual-prong flow time reduction strategy. First, I propose that the manufacturing organization review present flow times for the entire manufacturing process and recommend alternate near term flow time reduction strategies (such as increasing investments in human and/or capital equipment expenditures). The relative merit of these suggestions can then be determined by examining the marginal cost (cost of implementing flow time reduction proposal, usually a one time only cost) and the marginal benefits (reduced flow time cost, a recurring benefit) of each proposal.

Interestingly, implementation of near term flow time reduction proposals has the paradoxical effect of increasing corporate profitability but not improving manufacturing productivity[4]. In chapter 5, I show that a significant portion of direct manufacturing labor is attributable to variance-related activities. I also show that Engineering release quality affects the level of certain vital manufacturing variances (such as defects), thus indirectly impacting manufacturing productivity.

To improve manufacturing productivity and reduce manufacturing flow time in the long run, I recommend a continuous quality improvement effort which calls for Operations and Engineering to work together to raise Engineering release quality. Increased Engineering release quality should in turn reduce the level of manufacturing variances and improve

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[3] Please see chapter four for detailed discussions.

[4] In some cases, near term flow time reduction proposals may even decrease manufacturing productivity. See chapter four for detailed discussions.

manufacturing productivity. Manufacturing productivity improvements bring about three significant benefits: 1) reduced direct labor input per job, 2) decreased variable overhead, 3) lower flow time cost.

III. Adjust incentive systems to motivate flow time reduction[5]

With the above methodology for quantifying flow time cost and given the outline of the dual-prong flow time reduction strategy, there is nevertheless little assurance that there will be sufficient impetus within the organization to initiate and sustain continuous flow time reduction initiatives. I propose that the current incentive system, which emphasizes reductions of particular components of total product cost (such as labor cost), needs to be realigned to properly motivate organizational change.

Specifically, I suggest that flow time be included as part of the management performance objective. I propose that flow time cost responsibility be moved from the corporate level to the operating division level by charging flow time cost to the annual operating division budget. By moving flow time cost responsibility to the division level and having a common objective for the division Operations and Engineering organizations (to reduce flow time cost), I hope that these organizations will begin to recognize their respective impact on each others' productivity and initiate new joint efforts to reduce flow time. Specifically, with recognition of Engineering release quality's impact on variance levels and manufacturing labor productivity, Operations management should be willing to invest in the Engineering organization (through the budgeting process) in exchange for

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[5] Please see chapter five for detailed discussions.

commitments of improved Engineering release quality. This in turn lowers the level of manufacturing variances, thus decreasing manufacturing variance-related activities and increasing manufacturing labor productivity.

6.3 Boeing Initiatives

At the completion of my thesis research internship, I made presentations to numerous Boeing management teams on the results of my research. In addition, I covered specific recommendations which I worked on with many Boeing engineers and managers. The response from Boeing management was very positive. As the research and recommendations were conducted with the cooperation of senior Boeing 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 study will be performed on the 747 program to determine the impact of manufacturing variance on labor productivity. Next, the Finance department was assigned to quantify flow time cost for each flow day in the manufacturing process. Finally, the manufacturing organization at Everett was asked to initiate and implement flow time reduction initiatives for the 747 and the 767 airplane programs.

6.4 Application to Other Industries

The methodologies presented in this thesis on flow time cost and variance impact analysis are equally applicable in many different manufacturing environments. While the topic of inventory carrying cost is well known and widely written about, the specific methodologies presented in this thesis for understanding and quantifying the numerous components of flow time cost can hopefully help some companies better understand and assess this important manufacturing cost. In addition, the methodology presented in this thesis for analysis of variance impact on manufacturing productivity suggests new ways to examine the well known but difficult to assess impact of external manufacturing variances.

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