REDUCING FLOW TIME IN AIRCRAFT MANUFACTURING*

JACKSON S. CHAO AND STEPHEN C. GRAVES
The Boeing Company, Seattle, Washington 98124-2207, USA
A. P. Sloan School of Management, MIT, E40-439,
Cambridge, Massachusetts 02139-4307, USA

The assembly of aircraft is a labor-intensive process that exhibits a significant learning-curve effect and that requires long flow times and costly work-in-process inventories. This paper describes the production context, the cost of flow time in this context, and some of the causes for the long flow times. We then develop an argument for a firm to use improvements in labor productivity to reduce flow times. Boeing has implemented the recommendations from this research and has obtained significant benefits from reducing flow times.

(FLOW-TIME REDUCTION; AIRCRAFT MANUFACTURING)

In this paper we report the results from an internship performed by the first co-author at The Boeing Company. The internship was conducted as part of MIT’s Leaders for Manufacturing program, and ran from June 1990 through December 1990 in the New Airplane Division (now known as the Boeing 777 Division). The charge for the internship was to study the final assembly process of another Boeing airplane to discover lessons from its manufacturing and to make specific recommendations for the 777 program.

After learning about aircraft manufacturing the project quickly focused on manufacturing flow time and the questions of what does it cost, why is it so long, and what needs to happen to affect it. Doing things fast is a common theme in the best manufacturing practices and is advocated at length in the manufacturing literature, e.g., Dertouzos, Lester, and Solow (1989), Goldratt and Fox (1986), Hayes, Wheelwright, and Clark (1988), Schmenner (1988), and Stalk and Hout (1990). This research examines how these ideas apply to aircraft manufacturing and provides a case study for addressing flow-time issues.

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

We believe this study is a good example of action-oriented research that considers real operations with real problems and attempts to develop, extend, and apply new concepts.

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From this research, we can extract manufacturing principles that may be of generic value to other manufacturing contexts. Finally, this research can lead to significant, measurable impact for the company under study.

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

Planning of Aircraft Manufacturing

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

Description

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

The manufacturing flow time for a work center is the elapsed time (in work days) planned for a work center to perform and complete its required tasks. The flow time is the length of time that an airplane (or subassembly) will remain at a work center before moving to the next work center. Different work centers within the manufacturing sequence can have (and will have) different flow times.

The production cycle time is the elapsed time (in work days) between consecutive job completions for a work center or between airplane deliveries for the entire manufacturing system. Unlike manufacturing flow time, all work centers within the manufacturing system operate with the same production cycle time (i.e., at the same rate). An airplane manufacturer operating on a 3-day production cycle completes and ships an airplane from the production line every 3 days. Consequently, every work center also must complete work on an airplane every 3 days, no matter what the individual flow time of the work center is. Correspondingly, every 3 days, one new job enters each work center in the manufacturing process.

The number of job or tool positions required within a work center is the flow time divided by the production cycle time, rounded up to the next largest integer. So, a work center with an 8-day flow time and a 4-day production cycle has two job or tool positions. The work center has 8 days to complete its required tasks on each plane and ships a completed job to the next work center every 4 days. Similarly, a work center with 8 days of flow time operating on a 3-day production cycle requires three job or tool positions. The schedule has a plane entering the work center on 3-day intervals and a plane exiting
the work center on 3-day intervals; however, the arrivals and exits do not occur on the same day. As a result the number of job positions occupied by planes will vary between 3 and 2 over the 3-day cycle.

The number one flowchart depicts the exact sequence of every work center in the airplane manufacturing process (see Figure 1); there is a new number one flowchart for each new airplane program, model derivative, or new production rate. In Figure 1, the length of the jobs equals the flow time for the work center.

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

For each work center, a crew-size study determines the minimum, maximum, and optimal crew sizes on the basis of detailed examination and planning of the work content in a work center. The (so-called) optimal crew size is the number of workers at the work center that minimizes the direct labor input per job.

An Illustrative Example

Suppose that the number one production unit (i.e., the very first airplane) will require 800 labor hours to assemble a plane at a given work center. The traditional planning methodology would set the crew size to minimize the direct labor per job; suppose in this case the optimal crew size is 10 workers per job. Then, with one shift per day, the flow time for the work center is $800 \text{ h} / (10 \text{ workers} \times 8 \text{ h/worker day}) = 10 \text{ days}$.

If the production line were to operate on a 5-day cycle, we require two tool positions (10 flow days/5-day cycle). So, the work center initially will have 20 workers (10 workers per position) working on two jobs for 10 days each. Every 5 days a new job will move into the work center and a completed job will leave.
Suppose the flow time is not a multiple of the cycle time. For instance, if the cycle rate is one plane every 4 days and the flow time is 10 days, then there must be three positions. A new plane will enter the work center every 4 days and a completed plane will exit every 4 days: if new planes arrive at the work center on days 1, 5, 9, . . . , then planes complete the work center on days 3, 7, 11, . . . , where the plane that arrives on day \( x \) completes on day \( x + 10 \). As a consequence, half the time (2 out of every 4 days) the workforce is working on two planes, while the other half of the time they have three planes to work on.

If this work center is staffed with three crews of 10 workers, one per position, then each crew will be idle 2 out of every 12 days because job arrivals and exits are not synchronized. Thus, although the work statement calls for 800 labor hours per plane, this staffing plan with “optimal” crew sizes will incur 960 hours per plane (10 workers per position \( \times \) 3 positions \( \times \) 8 h/day \( \times \) 4 days per plane). To avoid this inefficiency, industrial engineering will relax the assumption of a dedicated crew per position and examine alternative ways to schedule the work in the work center. They will try to vary the crew size at each position with workers moving from position to position to achieve high labor utilization. In this example, at least 25 workers are required to produce a plane every 4 days (25 workers \( @ \) 8 h/d \( \times \) 4 days = 800 labor hours/4 days), which is the target for industrial engineering.

Alternatively, industrial engineering will examine flow times that are multiples of the cycle time and thus facilitate scheduling of the work, albeit likely with nonoptimal crew sizes. For instance, in this example it may be possible to have flow times of 12 days and three crews, each with nine workers. This staffing level incurs 864 labor hours for each plane.

Line of Balance Technique

The planning of airplane manufacturing, as described here, is an example of line-of-balance (LOB) analysis; see Schonberger (1985) and Iannone (1967) for a description. According to Schonberger, the LOB method is appropriate for the control of “limited-quantity production of a large-scale item.” The method entails four steps. The first step is to establish a delivery schedule or rate, e.g., a cycle time of one plane every 4 days. The second step is to develop a process plan, indicating the sequence of manufacturing steps and their lead times; Figure 1 is an example of a process plan. Within the process plan, one would identify control points; at Boeing, the completion of work at the work centers (known as control codes) are the control points. The third step is to monitor the progress at each control point against the delivery schedule, and the fourth step is to project what the future schedule is for each control point. At Boeing, these steps are performed through a variety of means. For a fixed-rate delivery schedule, each work center will “ship” its assembly or subassembly to the next work center according to a fixed schedule driven by material handling considerations; Boeing will monitor how often these shipments are done before all of the work has been completed at the prior work center. Projecting the future schedules for a work center is an issue only when there is a change in rate; when a rate change is being considered, there is an extensive plan made to roll out the change across the process. The description of this is beyond the scope of our paper.

Flow-Time Cost

In this section we identify three primary components of flow-time cost and discuss how to evaluate these costs in a context such as at Boeing. We then discuss the implications to the traditional production planning methodology at Boeing, and conclude with recommendations for how to incorporate flow-time costs into the methodology for production planning.
Flow-Time Cost Elements

We consider three types of flow-time costs: (1) inventory carrying cost, (2) revenue opportunity cost, and (3) variable tooling cost.

**Inventory Carrying Cost.** The inventory holding cost for carrying the work-in-process (WIP) inventory includes the opportunity cost for the money tied up in the inventory, plus storage costs, insurance, spoilage, and obsolescence costs. Usually, this cost is computed as the product of the inventory value and an inventory carrying rate, which includes at least the opportunity cost for money. For instance, in Figure 2 we show for a typical airplane how costs accumulate over the flow time for completing the airplane. The inventory holding cost for an airplane is found by multiplying this curve by the inventory carrying rate and then integrating over the total flow time.

We see from Figure 2 that a reduction in flow times will change the cumulative product cost curve and presumably reduce the inventory holding cost per plane. Thus, the first type of flow-time cost is the inventory holding cost for the WIP.

**Revenue Opportunity Cost.** In a market where there is substantial demand backlog for a company's product, there is a second type of cost called revenue opportunity cost. Boeing commercial airplane group maintains a multiyear order backlog. (For instance in late 1992, Boeing had an $90 billion, 3-year order backlog.) Revenue opportunity cost is the potential revenue from collecting sales revenue earlier if a shorter flow time results in earlier delivery of orders. For example, at the time this research was done (1990), demand exceeded supply in the commercial airplane industry. An airline ordering a Boeing 747-400 in 1990 was not going to get delivery of the airplane until approximately 1997. With airline passenger traffic predicted to grow at over 4% annually for the next decade, airline customers were eager to take delivery of newly designed, fuel-efficient airplanes as quickly as possible. Given this market environment, there were significant revenue opportunity benefits associated with shorter product flow time (and earlier product delivery).

**Flow Through versus Flow Back.** The possibility for a revenue opportunity benefit depends on the system response to a flow-time reduction. Consider a work center with 8 days of flow time and a 4-day cycle time, and suppose it reduces its flow time by 1 day. In isolation, the 1-day flow-time reduction at the work center brings about no tangible benefits. This is because the 1-day reduction simply has created a 1-day time buffer at the particular work center if there are no other schedule changes to the adjacent work centers.

![Cumulative Product Cost](image)

**Figure 2.** Cumulative Product Cost Curve for an Airplane.
To realize the benefits of flow-time reduction, either the upstream work centers need to delay their schedules to absorb the 1-day reduction or the downstream work centers need to accelerate their schedules to avoid the creation of a 1-day buffer. We term these responses as "flow back" or "flow through," respectively.

By flow back, we push the 1-day reduction back through all upstream work centers. If the specified work center now has a 7-day flow time, instead of 8 days, then it can receive its inputs 1 day later and still meet the original delivery schedule. Thus, the output schedule for the immediate upstream work center can be delayed by a day, which allows it to receive its jobs 1 day later, and so on. That is, the 1-day reduction in flow time allows all upstream work centers to shift their schedules by 1 day. The primary benefits are savings in inventory holding costs, as discussed in the previous section.

By flow through, we pull the 1-day reduction through all the downstream work centers in the manufacturing process. To accomplish this, all of the work centers downstream of the specified work center must compress their schedule by 1 day on the very first airplane when the flow through is to occur. That is, these work centers will receive this very first plane 1 day earlier than planned, namely, 3 days after the previous plane instead of the normal cycle of 4 days. These work centers need to complete their jobs within their normal flow times, and thus they deliver the plane to the next work center 1 day ahead of the original schedule. After this very first plane, the schedules for all subsequent work centers are thereby advanced by 1 day. However, because neither the flow time nor the production cycle time changes for these work centers, these work centers simply experience a 1-day compression when the flow-time reduction is pulled through for the first airplane; after that, the work centers should continue to operate as normal, but 1 day ahead of the original schedule.

Flow Through Illustration. We illustrate in Figure 3 how we can pull a flow-time reduction through the manufacturing process. From the figure, we see that the manufacturing process is operating on a 3-day production rate and consists of three sequential work centers A, B, and C, with flow times of 5, 4, and 5 days, respectively. Note that for the first two jobs in the production schedule, a new job is started and a completed job is shipped out every 3 days. Suppose that there is an opportunity to reduce the flow time at work center A from 5 to 4 days.

Table 1 below lists the start and completion dates for each of the work centers for all five jobs. On job number four, where the 1-day time buffer actually is taken out of work

![Figure 3. Production Schedule to Illustrate "Flow Through" Concept.](image-url)
TABLE 1
Start and Completion Dates for Five Jobs in Production Schedule

<table>
<thead>
<tr>
<th>Job</th>
<th>Work Center A</th>
<th>Work Center B</th>
<th>Work Center C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start Date</td>
<td>Completion Date</td>
<td>Start Date</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
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<td>2</td>
<td>3</td>
<td>8</td>
<td>8</td>
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<td>3</td>
<td>6</td>
<td>10</td>
<td>11</td>
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<tr>
<td>4</td>
<td>9</td>
<td>13 (14)</td>
<td>13 (14)</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>16 (17)</td>
<td>16 (17)</td>
</tr>
</tbody>
</table>

center A, work centers B and C had to accelerate their production schedules to flow through the flow-time reduction (the dates in parentheses in Table 1 are the original start and completion dates for each work center under the previous, longer flow time). After the one-time schedule acceleration for job number four, work centers B and C settle back to their regular production pace, starting and completing each job 1 day ahead of the old schedule.

This analysis applies similarly to a more complicated manufacturing process involving an assembly network of work centers (e.g., Figure 1). Then the schedule needs to be accelerated for all work centers downstream of the specified work center and for all work centers on branches that join the network downstream of the specified work center. This is necessary to move the delivery schedule forward by the amount by which the work center’s flow time has been reduced.

Advantages and Disadvantages of Flow Through versus Flow Back. A company can choose to flow back or flow through the buffer created by the flow-time reduction. Flow back simply requires that upstream work centers start later; there is no compression of the schedule and implementation is far easier than flow through. Because there is no change to the delivery schedule for the final product, the only savings are the reduction in inventory carrying costs because of a shorter flow time. Flow through shifts the production schedule ahead by the length of the flow-time reduction and achieves revenue opportunity cost savings as well as inventory carrying cost savings. By choosing flow through, a company will have to accelerate the production schedule for a preselected job to pull the time buffer created by the flow-time reduction through the manufacturing process. This requires both careful planning and additional manufacturing costs, such as overtime, to accomplish the acceleration of the preselected job. Once this is done, all subsequent jobs follow the original schedule, shifted forward by 1 day.

Calculating Revenue Opportunity Cost. Calculating revenue opportunity cost for an airplane program requires knowledge of the cycle rate, selling price of the aircraft, customer prepayment factor (if applicable), and relevant interest rates or the firm’s cost of capital. Consider an example for an airplane with a sales price of $50 million. Suppose that there is no prepayment factor and that currently there is a multiyear backlog for this airplane. Customers make their payment at the time of delivery and are willing to accept (and pay for) early delivery. The company is operating at capacity and produces one airplane every 4 days.

Consider a proposal to reduce flow time by 1 day. If the company pulls the flow-time reduction through the manufacturing process, it will then ship product to each of its customers 1 day earlier. In terms of cash flow, this will enable the company to collect its $50 million revenue from each customer a day earlier than under the current, longer flow time. This shift in the revenue stream generates revenue opportunities for the company in the form of either simple interest or internal investments. For instance, at an annual interest
rate of 10% and a working calendar of 250 working days/y, 1 (working) day of interest on $50 million is $20,000. Over the course of a year, with a 4-day production cycle, the revenue opportunity from the 1-day flow-time reduction amounts to $1.25 million. The savings of $1.25 million per year will recur for the life of the plane’s backlog or until the production rate is reduced. Furthermore, any additional reduction in the flow time that can flow through the process will generate revenue opportunity savings of $1.25 million per year for each day; and any flow-time reduction, regardless of whether it flows through or back, yields savings in inventory carrying costs.

**VARIABLE TOOLING COST.** Variable tooling costs are especially important in a high capital, labor-intensive manufacturing environment such as at Boeing. These costs result from the purchase and maintenance of production tools and equipment for the manufacturing process; we illustrate here how these costs depend on flow times.

A work center with 8 days of flow time and a 4-day production cycle requires two tooling positions. If the production rate increases to a 3-day production cycle, the number of required tooling positions increases to three and a new tool has to be purchased, say at a cost of $1.2 million. However, if the work center can reduce its flow time to 6 days, then the tooling requirement for the work center remains at two when the production cycle decreases from 4 to 3 days. Therefore, in this example, flow-time reduction from 8 to 6 days saves $1.2 million in tooling costs.

Variable tooling costs (and savings) increase in fixed increments that depend on the production cycle time and the flow time for the work center. In the example, reducing the flow time from 8 to 7 days does not impact the tooling costs when the production cycle changes to 3 days; the number of required tools remains at three. That is, a 1-day flow-time reduction has no variable tooling benefit in this example, whereas a 2-day flow-time reduction saves $1.2 million in variable tooling savings.

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

Long flow times also decrease a company’s capability to respond quickly to shifting market demand. At Boeing, because all production is to customer order, long flow times limit the company’s ability to respond to change requests from customers. Because of the long manufacturing flow time, Boeing will encourage their customers to decide exactly what they want long in advance of delivery. However, because this is not always realistic, Boeing will incur additional costs, because of the disruption of the normal manufacturing process, to accommodate the inevitable changes from customers.

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

There has been limited visibility and awareness of the costs of flow time in the planning methodologies practiced at Boeing. To appreciate this, we offer the following observations to provide some perspective.

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

In Boeing's management accounting system, there has been little recognition of cost associated with manufacturing flow time. The lack of flow-time cost visibility, coupled with the importance of completing jobs to schedule (while maintaining the capability to manage unforeseen disruptions) and close management scrutiny on workforce head count, all contribute to the practice of managing the workforce head count, at the expense of manufacturing flow time. Consequently, as the total labor required within a work center decreases because of worker learning, the production planning methodology has relied heavily on head-count reductions to realize learning-curve benefits; at the same time the planning methodology maintains flow time to insure that work centers can meet the strict production schedules and accommodate unforeseen disruptions.

In the remainder of this section, we argue that there are trade-offs between the workforce level and the flow times, and that these trade-offs need to be examined explicitly as part of the production planning. In particular, we discuss two immediate implications to Boeing's production planning methodology that result from an awareness of flow-time cost.

**DETERMINATION OF WORK CENTER DESIGN PARAMETERS.** In determining the flow time and the staffing level for a work center, production planning needs to adapt its methodology to evaluate all relevant costs, rather than focus primarily on labor efficiency and capital investment.

For example, consider a work center with a 10-day production cycle, a 20-day flow time, and with a total staff size of six. The labor input is 480 hours per job. The present operation minimizes labor input per job by operating with the optimal crew size while protecting the schedule by having two jobs in process for smoothing unforeseen disruptions. Now, consider a proposal to reduce 2 days of manufacturing flow time at the work center by adding two more workers so that the labor input is 640 hours per job. The traditional production planning methodology would view the flow-time reduction as a bad proposal because of the increased labor cost per job. However, by incorporating flow-time costs, this proposal actually might be very beneficial because it reduces inventory carrying cost at the work center by 2 days, and depending on the implementation, may result in revenue opportunity cost savings.

**REALIZATION OF PRODUCTIVITY IMPROVEMENTS.** In a manufacturing environment where there is significant worker learning, the labor input required within each work center decreases as a function of the number of airplanes produced [see Chao (1991) for an example].

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

**PROPOSED PRODUCTION PLANNING METHODOLOGY.** We have proposed a new methodology for utilizing worker productivity improvements that evaluates the possibility of reducing flow time. We illustrate this approach with an example.

Suppose a work center initially requires 40 labor days, and operates with 10 flow days and two tooling positions to meet a 5-day production rate. There are eight workers working
in the work center, four for each tooling position. Through worker learning, suppose the average labor content decreases to 10 labor days by unit 256; however, because of manufacturing variances, labor content varies from plane to plane and can range up to 16 labor days per plane. Assume that because of projected market demand, the production cycle rate is to increase to a 2-day cycle. Table 2 lists three alternative scenarios of utilizing the productivity improvement benefits and their respective impact on flow time, labor head count, and tooling positions.

From Table 2, we see that the three scenarios have drastically different labor content per job. In scenario one, where the work center has 10 flow days and five job positions, the supervisor can shift workers between jobs (from easier jobs to harder jobs) and smooth the work variability between incoming airplanes [see Chao (1991) for more discussion]. In scenario three, where the work center has only 2 flow days and one job position, the supervisor must staff at a level capable of completing even the most difficult jobs within the production schedule; because the labor content per job can range up to 16 labor days, the supervisor has to staff the work center with eight workers so that 16 labor days are available per job. Scenario two is a mixture of the two extremes.

To choose from these scenarios requires knowledge of the flow-time costs as they apply to this work center, plus the cost of labor. More often than not this evaluation favors the scenario that reduces flow time the most, at the expense of labor productivity. This is counter to prior practice, which has not considered flow-time cost and has focused on minimizing labor content.

**IMPLICATIONS OF PROPOSED METHODOLOGY ON NEW AIRPLANE PROGRAM.** In a new airplane program, where facilities have not been built yet, the proposed production planning methodology has significant impact. In particular, realizing productivity improvements via flow-time reduction will result in significantly shorter flow times as the number of airplanes manufactured increases. Therefore, as the new airplane gains market acceptance and approaches maximum production rate, the shorter flow time will reduce the costs for facilities and tooling, as well as providing reduced inventory carrying cost and revenue opportunity cost. For a new airplane program, where new capital investments add up to hundreds of millions of dollars, the proposed production planning methodology can bring about significant program savings.

**Impact of System Variance on Direct Labor Input**

In the previous sections, we quantify the cost of flow time and examine the trade-off between flow time and labor content within aircraft manufacturing. In this section, we consider how to avoid this trade-off by attacking both flow time and labor content simultaneously. In particular, we analyze the impact of *system variances* on labor input, and indirectly on flow times. We define system variance as the factors or elements within the manufacturing environment that affect the execution of baseline manufacturing operations. Examples of variances in the manufacturing environment are

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>Three Different Ways to Realize Productivity Improvements</th>
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<tbody>
<tr>
<td></td>
<td>Scenario 1</td>
</tr>
<tr>
<td>Flow time</td>
<td>10 days</td>
</tr>
<tr>
<td>Cycle time</td>
<td>2 days</td>
</tr>
<tr>
<td>Tooling positions</td>
<td>5 positions</td>
</tr>
<tr>
<td>Staffing</td>
<td>5 workers</td>
</tr>
<tr>
<td>Average input/job</td>
<td>10 labor days</td>
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</tbody>
</table>
engineering changes, part shortages, job rework, part rejections, and various product options.

At Boeing, significant portions of total manufacturing labor input are attributable to system variances. In this section, we present a working hypothesis regarding the effects these variances have on manufacturing labor input. We use regression to test the validity of the working hypothesis and to estimate the effects of the variances on manufacturing labor input.

The regression analyses support the working hypothesis that relates actual labor input to a baseline work time and the effects of external manufacturing variances. The regression focuses improvement efforts on the high-impact variances instead of diverting attention onto all the variances. Eliminating or reducing these system variances leads to productivity improvements (lower labor input), which brings about the following three significant benefits: (1) lower direct labor cost, (2) decreased variable labor overhead, and (3) reduced flow-time cost. The improved labor productivity leads to reduced flow-time cost because a significant portion of the flow time is caused by 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 can be taken out without incurring additional risk to the schedule.

**Working Hypothesis**

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

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

We model the actual manufacturing time at each work center as the sum of the BWT and the cumulative effect of the various external system variances. We will test the validity of this working hypothesis by means of a multivariate regression analysis.

**Data Collection Methodology**

To test the validity of the working hypothesis, the first co-author studied an existing Boeing airplane program, which we call the 7A7, to protect its identity and collected actual direct labor data and system variance data for 50 consecutive Boeing 7A7 airplanes.

**Major Shops.** During data collection, we uncovered a difference in the way that data for direct labor hours and data for the system variances are kept. The direct labor hours are recorded and stored at the work center level, whereas the system variance data are collected, aggregated, and reported at the "major shop" level. These major shops, which are collections of work centers in the manufacturing process, are the major operational units of the manufacturing organization. The following are the four major shops within the manufacturing sequence: (1) body structures, (2) wing structures, (3) join and installations and final assembly, and (4) field operations.

To insure compatibility of data, we aggregated the labor-hours data for the work centers by the four major shops. In addition, we aggregated all of the data for the four major
shops to form a data set for analysis at the airplane level. This was done to get a macroview of the overall impact of system variance effects on manufacturing direct labor input.

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

Description of Regression Analysis

A total of five separate analyses were run for the Boeing 7A7 program. The first analysis is the regression of direct labor hours against about 30 system variances for the total airplane and provides an analysis of variance impact on the entire 7A7 manufacturing process. The other four analyses are for assessing variance impact on each of the four major shops in the manufacturing process. We will report here only the results from the total plane regression; the regression results for the four major shops are similar to that for the total airplane but differ according to differences in the operating characteristics of these shops. [see Chao (1991) for details]

To build an accurate model of direct labor hours, the first author consulted extensively with senior managers and industrial engineers. This consultation helped to determine the relevant manufacturing variances to include in the regression analyses, as well as to insure that the results of the analyses made sense and were consistent with their experience. Initial efforts attempted to regress over 30 different system variance variables as independent variables against the dependent variable, direct labor hours. This approach resulted in unsatisfactory solutions because many of the independent variables were correlated.

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

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

Statistical Regression for Total Airplane

In Table 3 we give the results for the regression model for the total airplane, namely, the independent variables, their coefficients, and their standard errors. We do not report

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer introduction</td>
<td>2,964</td>
<td>769.7</td>
</tr>
<tr>
<td>Part shortage</td>
<td>3.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Production revision request</td>
<td>276.7</td>
<td>28.3</td>
</tr>
<tr>
<td>Model 2</td>
<td>-2,247.8</td>
<td>878.4</td>
</tr>
<tr>
<td>Defects</td>
<td>1.3</td>
<td>0.46</td>
</tr>
<tr>
<td>log 2(x) of Unit number</td>
<td>-47,732.6</td>
<td>8,117.8</td>
</tr>
</tbody>
</table>
the intercept for the model, in that it represents an estimate of the direct labor hours for the first plane and hence is proprietary. We will define the independent variables below.

The top-level airplane regression explains 96% of the variability in the dependent variable, direct labor hours ($R^2 = 0.96$). Furthermore, all of the variable coefficients are consistent with our prior expectations.

The customer introduction variable is a binary variable, which denotes that a particular airplane is being delivered to a new airline customer. This usually requires quite a bit more direct manufacturing input because of the learning required to satisfy the custom specifications for the first airplane for a new customer. In addition, during the customer introduction process, the airline customer usually is more exacting in inspections and thus requires more time during the acceptance process. From the regression, we see that a new customer results in nearly 3,000 additional direct labor hours.

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

The baseline airplane model of the regression, because of its popularity in the 50-plane sample, is the 7A7 model 3. The model 3, which is approximately 30 ft longer than the model 2, requires more assembly and integration time than the model 2. The model 2 variable is a binary variable that takes a value of one for model 2 and a value of zero for model 3. As expected, the regression model indicates that the model 2 airplanes require 2,200 less labor hours to manufacture.

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

Finally, the log 2 of unit number variable captures the learning effect. The independent variable is the log, base 2, of the cumulative production number of the plane; for instance the 32nd plane produced by the line would have a value of five for this variable. The regression coefficient for this variable signifies by how much the direct labor hours per plane go down when the production count doubles. As expected, we see a strong learning effect for the total manufacturing labor input as a function of the number of airplanes produced.

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

**CONSTRUCTION OF VARIANCE PIE CHARTS.** From the statistical analysis, we can construct a "variance pie chart" to show the relative impact of system variances on direct labor hours. In particular we determine what percentage of the total direct labor hours are caused by each of the system variances from the regression. For instance, from the regression for the total airplane, suppose that the average number of defects per plane is 100. Then, each plane had an average of 130 labor hours caused by defects; if each plane had an average
of 5,000 direct labor hours in total, then defects are responsible for 2.6% of the direct labor. In this way, Boeing has used the regression results to determine the relative contributions of the system variances to the total direct labor and to identify the high impact "vital few" variances. We have found that displaying these percentages with a pie chart is a very effective way to highlight the most important system variances. Unfortunately, because of the proprietary nature of the data, we cannot include the variance pie charts for the four major shops and for the entire final assembly process of the Boeing 7A7 airplane.

**Strategy for Reducing Defects.** The regression analyses show that, consistent with the Pareto principle, a few variances account for the majority of the impact on the direct manufacturing labor input for the assembly of airplanes. Simply presenting these results, however, does not always point to particular strategies for reducing the level of these variances. We summarize here the results from further analysis that produced a strategy for reducing one of the significant variances, namely, defects; see Chao (1991) for more details.

In the regression analysis, defects accounted for a significant portion of direct manufacturing labor input. To develop a strategy for reducing defects, we hypothesized that the engineering organization has a major effect on the level of defects and, thus, plays an indirect role in determining the total direct labor input. That is, certain engineering activities such as engineering changes and engineering errors disrupt the normal work flow in a work center and increase the likelihood of worker error, i.e., defects. To test this hypothesis, we again employed a regression analysis to relate statistically two engineering actions to the number of defects. The value of this analysis was that it provided evidence to support the hypothesis, namely, that two engineering variances were driving the number of defects. In particular, we found that engineering has an important indirect impact on direct manufacturing hours through the effects that the quality of engineering release has on high-impact variances such as defects.

**Impact**

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

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

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

From these efforts, Boeing has achieved significant benefits. The manufacturing organization has removed several days of flow time from the 7A7 and the 7B7 programs. These reductions came primarily from converting the productivity improvements from learning into flow-time reductions rather than head-count reductions. Some of the flow-time reductions have been pushed through the manufacturing process to permit the acceleration of deliveries of airplanes. Within the first year, Boeing delivered one additional 7A7 and one additional 7B7 and collected the net profits from these additional deliveries. These reductions also have contributed to reducing WIP inventories and have generated net savings in inventory holding costs of tens of millions of dollars over a 4-year period.

More important than these immediate benefits is the fact that these efforts are continuing and the paradigm at Boeing for manufacturing planning is changing. Factory management and industrial engineering continue to drive the efforts to reduce flow time in the factory. The manufacturing organization recognizes the cost of flow time and it is being integrated as part of their planning methodology and their performance management system. Finally, the first assignment for the first co-author on joining Boeing was to assume responsibility for inventory reduction for the next Boeing commercial airplane, the 777; so these ideas and concepts have been applied to this new program.¹

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