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4 Learning by New Experiences: Revisiting the Flying Fortress Learning Curve

Kazuhiro Mishina

4.1 Introduction

It has often been argued in recent years that the firm is a dynamic learning organization. This view holds that the firm not only converts factors of production into a salable product, as modeled in the neoclassical theory of the firm, but also learns over time how better to do so. If learning and production indeed occur jointly, firms preoccupied with the optimization of production alone are shortsighted and must be encouraged by either management or public policies to invest in learning. Is there merit to considering yet another challenge to the traditional theory of the firm? The issue, of course, is not whether the firm learns at all. That is a question of semantics. The real issue is materiality. Do the productive powers of labor increase above and beyond the level predicated on the theory of the firm, and is it sensible to attribute that increase, if any, to learning on the part of the firm? The first of these two questions has been addressed by the literature on the learning curve, albeit incompletely, and the second of the two remains an open question. The gaps that exist in the story of firm-level learning are the focal point of the essay that follows.

This essay, at its core, visits a factory—one of the twenty-two airframe factories studied by Alchian (1963) in his pioneering work of the learning-curve literature—and, aided by the recent advance in the study of operations management, examines what happened behind an authentic learning curve inside the black box of the firm. The factory is Boeing's Plant No. 2 in Seattle, Wash-

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ington. This was the primary production site of the famous B-17 heavy bomber, the Flying Fortress, during and prior to the Second World War. This particular production program offers many advantages for a study of this nature. Being a wartime program, it ran for an exceptionally short span of time. The program data therefore escaped external interference such as generic technological progress in the society at large. The B-17 program, moreover, is relatively well documented. The B-17 was virtually Boeing's sole product when it was in production, and its sole customer was the government, which had to justify the cost of heavy bombers vis-à-vis Congress. One would be hard-pressed to find a more attractive case to study when the central theme is firm-level learning.

4.2 The History and the Problems of the Learning Curve

The notion of learning formally entered economics with the discovery of the learning curve. Curiously, however, the learning curve itself was born when the engineering discipline tried to rewrite the theory of the firm in earnest. T. P. Wright, the director of engineering of the Curtiss-Wright Corporation, was apparently inspired by the mass production of automobiles as well as the dream of family airplanes when he began to plot out "the effect of quantity production on cost" (Wright 1936). The resulting graphs, reported in the *Journal of Aeronautical Sciences,* showed a decreasing convex curve with cost—or its components—on the vertical axis and the sequence number of the airplane on the horizontal axis. When converted to logarithmic scale, the graphs looked linear, suggesting not only predictability but also specific mathematical relationship: labor required per unit—or, interpreted more casually, unit cost—is a negatively sloping log-linear function of the cumulative volume of production. It is this mathematical formulation that was later named variously the learning curve, experience curve, and progress function. All three refer to the same phenomenon while emphasizing a slightly different aspect: the process, cause, and outcome of the cost behavior, respectively. In the studies that followed, the formulation fit data quite well in a wide range of industries including, but not limited to, shipbuilding, machine tools, specialty chemicals, and semiconductors.

The learning curve thus established empirically resembles the average-cost function of the traditional theory of the firm in that both strip the firm all the way down to two variables and formalize a widely held belief among industrialists: the unit cost goes down as a firm or a factory makes more of the same product. The learning curve, however, departs from the traditional theory of the firm in two respects. First, it replaces the variable on the horizontal axis. In lieu of the rate of output (output per period), to which economists are accustomed, it inserts cumulative output. Interestingly, though, Wright himself was quite possibly indifferent to the choice between the two variables. He was concerned with the cost estimate of the Nth airplane in production and always labeled the horizontal axis of the graphs N—the sequence number of the airplane—and not as cumulative output. Moreover, he perhaps had no choice but to use the sequence number, as opposed to the rate of output. Given the long time needed to build each unit of an airplane and the small number of units demanded by the market for an airplane, it was not very practical to gauge the rate of output for any natural unit of time, such as week, month, and year, unless a reliable method to measure a fraction of an airplane was devised. In Wright's data, N fell short of 150 in one case and 40 in the other despite years of data gathering. Second, the learning curve departs from the traditional theory of the firm in its adoption of a specific functional form. Although the log-linear formulation was justified only by computational convenience and subsequent good fit, it enabled the learning curve to spell out the cost of every unit in the production sequence and the associated factor requirements once its two parameters—the initial cost and the rate of learning—are estimated.

The two points of departure—the use of cumulative output on the horizontal axis and the specification of the functional form—are thus arbitrary in terms of how they came into being. But it is precisely these two features that led to the widespread appeal of the learning-curve formulation. For one, they together eliminate uncertainty as well as dependence upon decisions, such as setting the rate of output, from the estimation of the unit cost and factor usage, thus opening an avenue to a new possibility of planning operations (Andress 1954) or formulating strategy (Boston Consulting Group 1972) around these deterministic estimates. Those who wish that the pragmatism of engineering ruled management are finally vindicated. For another, cumulative output makes sense as a proxy variable for some sort of production-related experience and, therefore, permits plausible interpretations of the learning curve. In one such interpretation, the learning-by-doing hypothesis, cumulative output is thought to measure the amount of on-the-job practice performed by the direct workers and, consequently, the level of skills they bring to bear on the work they do (Hirschmann 1964). Alternatively, one may think of cumulative output as growing in proportion to the feedback engineers receive from the shop floor regarding the robustness of the process or the manufacturability of the product they developed (Hirsch 1952; Conway and Schultz 1959). Then, the learning curve represents the level of engineering refinement and, in turn, the ease with which direct workers of a given skill level perform their task. Be it direct workers, engineers, or both who actually learn in the firm, those who hold that experience is the mother of improvement are vindicated by these interpretations of the learning curve.[1]

The learning curve is interesting because it seemingly captures a force that

1. If cumulative output merely represents experience, there may well be other proxy variables that are equally good. The one that has been studied most on this line of reasoning is the elapsed time (Fellner 1969). This alternative model makes sense if the stimulus of learning is independent of production and bound by the passage of time. As opposed to learning by doing, one may call it a model of learning by thinking. The same contrast is often framed as induced learning versus autonomous learning (Levy 1965; Yelle 1979; Dutton and Thomas 1984).

is not present in the traditional theory of the firm. However, a question is inevitable. Does it truly mark a departure from economies of scale—a central force shaping the average-cost function in the theory of the firm? Is it not merely the division of labor in disguise? Despite the seriousness of the question, the learning-curve literature offers no clear-cut answers.

The problem is twofold. First, when Wright discovered the learning curve, he was in fact walking familiar territory covered well by Adam Smith. He wrote, "The factors which make possible cost reductions with increase in the quantity produced are as follows: the improvement in proficiency of a workman . . . less changes to disconcert the workman . . . greater spread of machine and fixture set up time . . . ability to use less skilled labor as more and more tooling and standardization of procedure is introduced" (Wright 1936, 124). One may contrast this quote with an earlier well-known observation. Adam Smith, in his inquiry into the causes of the wealth of nations, opened his text with an account of contemporary pin manufacturing practice, in which an ordinary factory employed ten workers to staff approximately eighteen distinct operations and produced upwards of 48,000 pins a day. This amounted to 4,800 pins per worker per day although, he wrote, the workers were not capable of making 20 pins each a day alone. Smith reasoned that the dramatic improvement in the productive powers of labor was due, directly, to a proper division and combination of the different operations and, indirectly, to a large scale of operations—and a large market size—which permitted the division of labor in the first place. He thus established scale—usually measured by the flow rate of output, such as 20 pins a day or 48,000 pins a day—as the most important variable in the cost function or, more broadly, in the theory of the firm. Interestingly, Smith ([1776] 1976, 11) attributed the effect of the division of labor to three factors: "first to the increase of dexterity in every particular workman; secondly, to the saving of the time which is commonly lost in passing from one species of work to another; and lastly, to the invention of a great number of machines which facilitate and abridge labor, and enable one man to do the work of many." These three points correspond almost perfectly to Wright's passage explaining the reasons for the declining cost of airplanes.

Second, the learning curve and the economies of scale are virtually indistinguishable in the majority of econometric studies. The reason is the collinearity between their right-hand-side variables, that is, cumulative output and the rate of output, since the former is nothing but the latter summed over time. Collinearity is especially strong where the rate of output follows an upward trend, as cumulative output always does by definition, and the unit cost or labor hours a downward trend: a pattern predominant in the data used in the learning-curve studies. Thus, it is generally difficult, if not impossible, to properly decompose whatever variations there are in the unit cost data into the part explained by the rate of output, that is, the effect of scale, and the part explained by cumulative output, that is, the effect of learning, so long as the effort to do so relies exclusively on numerical data analysis. Herein lies the promise of detailed case studies.

4.3 The B-17 Program

The Boeing B-17 heavy bomber, known otherwise as the Flying Fortress, was the first four-engined, all-metal, midwing monoplane.[2] It served the U.S. Army Air Forces as a workhorse during World War II. It received much attention, both during and after the war, in part because it was one of the few experimental bomber designs that were deemed combat-worthy when the war broke out in Europe and President Franklin D. Roosevelt suddenly called for 50,000 airplanes a year. The B-17 production program, and in particular its efficiency and ramp-up speed, thus took on a special meaning as a crucial test of the nation's combat readiness. It was in this context that the Air Materiel Command (1946a) later studied this program extensively as an integral part of its postwar planning efforts and issued a comprehensive report on the program performance. This case-study report is the primary source of information for the analysis that follows. The report was compiled on the basis of extensive interviews of Boeing personnel,[3] and the Boeing Aircraft Company concurred that "[a]ll corrections and revisions recommended by us were embodied in this report except those concerning the section on Management"—a section of little interest for the purpose of this essay. The report is generally approving of the choices made by the company during the war, and concludes that the B-17 program's rate of acceleration "compares favorably with that reached by other manufacturers of heavy bombers throughout the country" (ix).

The B-17 began its life in July 1935 as the Model 299—Boeing's answer to an army air corps circular calling for a new multiengined bomber. Boeing developed a semimonocoque all-metal bomber with four engines, by far the largest and boldest entry in the competition.[4] Boeing, however, was disqualified because the only Model 299 it built crashed and burned during the first official test flight. The contract was awarded to a sister model of the Douglas DC-3: a two-engined airplane that was to set the standard for commercial aviation. Boeing's risk-taking was nonetheless rewarded with a small contract for

2. A monoplane has only one pair of wings. A biplane has two pairs of wings, one above and one below the fuselage.

3. The report acknowledges the help it received from Boeing's key officers. Their titles are listed as Engineering Historian, Tooling General Superintendent, Liaison Engineer, General Supervisor Training, Assistant to Operations Manager, Assistant to Executive Vice President, Director of Industrial Relations, Assistant to Chief Project Engineer, Assistant to Chief Cost Accountant, Material Manager, Plant Facilities Manager, Personnel Manager, BDV Committee Member, Assistant to the President, Chief Cost Accountant, Operations Manager, Business Office Superintendent, Analyst & Statistician, Quality Manager, Assistant to Production Manager, Superintendent Manpower, Chief Engineer, and Executive Vice President.

4. An airplane with a monocoque structure lets the skin absorb all the stresses to which it is subjected.

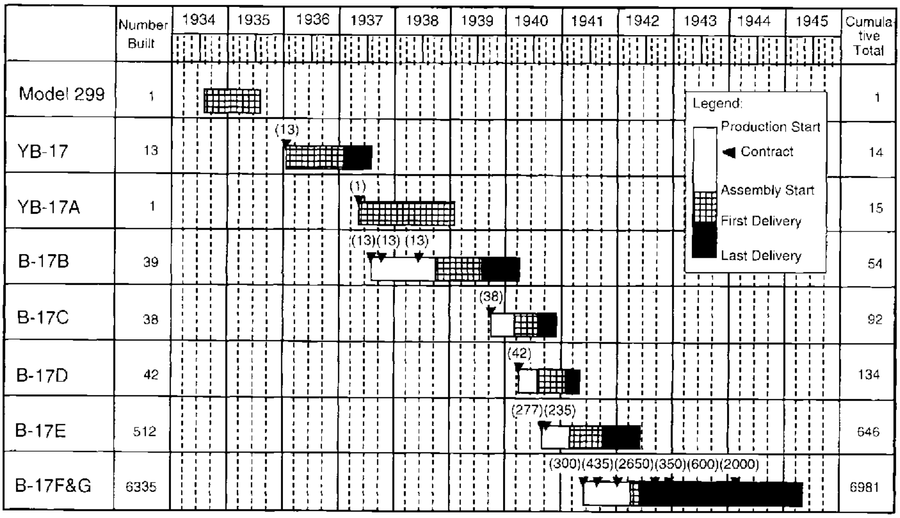

Fig. 4.1 The variations of the B-17

thirteen test units. The YB-17 thus came to life with a new and improved engine, and the B-17 series, despite the criticism in Congress that this heavy bomber was too large and too expensive, eventually evolved through nine official designations (fig. 4.1).[5] Of the nine designations, the last three, E, F, and G, were produced in large numbers and flown over combat theaters. The other designations up to D were more of a prototype, pushing the limit of the basic design. The cruising speed and altitude of the B-17 increased constantly from the Model 299 to the D designation, and thereafter remained unchanged. Between D and E, the rear fuselage was enlarged to accommodate more gunners and heavier defensive armament. Once the basic design was frozen with the B-17E, the subsequent designations differed from E predominantly in terms of added-on armament.[6] Indeed, Boeing internally categorized E, F, and G as "Model 299O" as if they were identical, and so did the Royal Air Force as "Fortress II." In the remainder of the essay, these three designations are collectively identified as the production version of the B-17. Boeing built a grand total of 6,981 units of the B-17, of which 6,847 units were, according to this definition, the production version.

Boeing built almost all B-17s in its main plant (Plant No. 2) in Seattle, which started its life in 1935. Plant No. 2's achievement in both ramp-up speed and productivity is impressive by any standards. Being one of a few proven bombers at the outbreak of the war, the B-17 was called upon as an implement of strategic bombing. The War Department issued a letter of intent ordering 512

5. For the history of the heavy bomber program, see Craven and Cate (1955), Holley (1964), and Rae (1968).

6. Davis (1984), for example, explains the evolution of the airplane in more detail.

B-17Es in July 1940, and thereby made Boeing begin its planning for plant, tooling, and workforce expansion. The delivery of the production version began with five units in September 1941. Monthly production then rose steadily, reaching 100 units in the course of July 1942 and 200 units in the course of May 1943. Plant No. 2 recorded peak production in March 1944 when it delivered a staggering total of 362 units. In the next month, Boeing continued production but also began the conversion of Plant No. 2 from the B-17 to the newer and larger B-29. The effort accelerated in February 1945, but the war ended before the B-29 saw mass production.[7] Plant No. 2 delivered its last 32 B-17Gs in April 1945.

The B-17 was a complex airplane to build, requiring tolerances as tight as 0.005 inches and more than six miles of wiring. The five airplanes delivered in September 1941 consumed on average 142,837 direct labor hours per airframe: the equivalent of approximately 71 worker-years.[8] Thereafter, unit direct labor hours followed a declining trend. They bottomed out in August 1944 at 15,316 hours, almost one-tenth of what had been needed 35 months earlier. Productivity suffered during the cutback phase, and the 100 airplanes delivered in December 1944 embodied 21,357 direct labor hours per airframe. Nevertheless, it is incontrovertible that Plant No. 2 exhibited a dramatic learning effect as measured by the direct labor hours needed for each airframe. The government accordingly reduced the price it paid to Boeing from $242,200 for the first B-17E to $144,824 for the last B-17G despite the vast improvement made to the airplane in between.[9] Figure 4.2 shows a plot of monthly output and unit direct labor hours.

With the information in figures 4.1 and 4.2, it is possible to draw a classical learning curve for the B-17 program. The relevant data here cover the 40-month period between September 1941 and December 1944.[10] The dependent variable of interest is the unit direct labor hours, l_t, which is shown on the vertical axis of figure 4.2. This variable measures the work hours logged by the direct workers of Boeing and its subcontractors, averaged over all airframes that were delivered to the government in month t.[11] One may argue that the unit cost is superior to l_t as dependent variable, but l_t is a major driver of the unit production cost of the airframe.[12] Moreover, where production is labor intensive, l_t makes a cleaner measure of the true unit cost than the accounting cost,

7. See Hershey (1944) and Boeing's 1945 annual report.

8. An airframe here refers to an airplane less such government-furnished items as engines and armament.

9. Note that the total cost of an airplane is dominated by the material cost, and explained only partly by the labor cost.

10. The delivery of the B-17G continued through the first four months of 1945, but data reporting did not.

11. See Asher (1956), Reguero (1957), and Alchian (1963) for a comprehensive account of the original source and the definition of the data.

12. Reguero (1957), for example, estimated that wages represented 60 percent of the unit cost of an airframe.

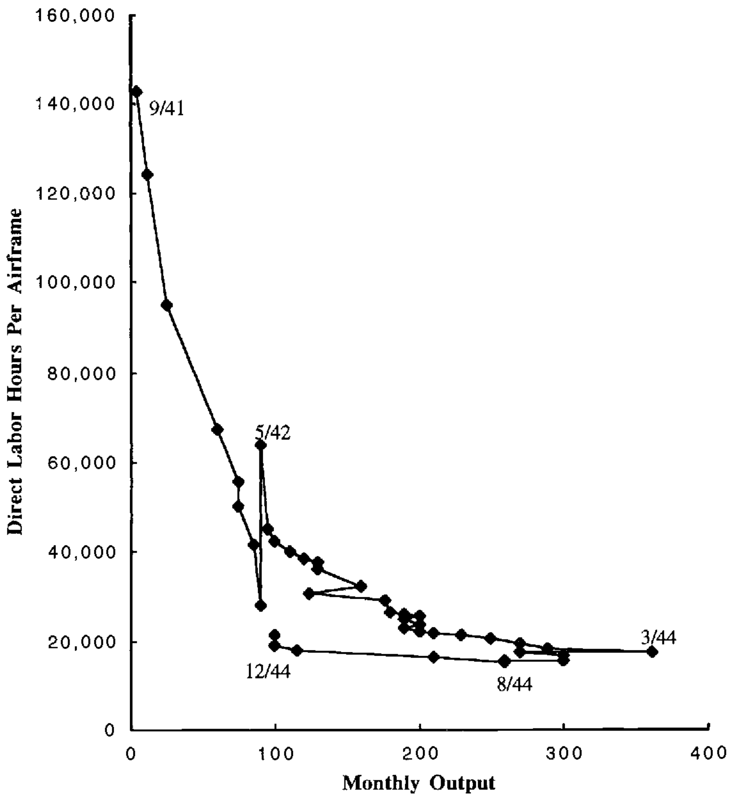

Fig. 4.2 The raw data

which rather arbitrarily allocates overhead expenses and fixed costs (Wright 1936).

The classical learning curve is written as

(1) $$\log l_t = a + b \log Y_t,$$

or $l_t = aY_t^b$, where Y_t stands for the cumulative output, or $Y_t = \sum_{s=1}^{t} X_s$, where X_s in turn stands for the output in month s. Applying this formulation to the B-17 data, column 1 of table 4.1 reports the result of the popular regression using ordinary least squares (OLS). It indicates that the best estimate of b is $-.472$, that is, every doubling of cumulative output gives rise to 27.9 percent decline in the unit direct labor hours. The coefficient of determination adjusted for the degree of freedom, $\bar{R}^2$, is respectably high and the estimate of parameter b is statistically different from zero. This is where analysis usually ends and speculation begins concerning the implications of the learning curve to policymakers, business executives, and operations managers.

The problem is that such an estimate of the learning curve is not unbiased

Table 4.1 **Linear Regression of log l_T**

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Constant	6.001	6.263	6.534	6.632	4.629	6.741	6.621
$\log k_T$		−.581[a]	−.488[a]	−.567[a]	−.735[a]	−.902[a]	−.547[a]
		(.083)	(.109)	(.089)	(.079)	(.210)	(.093)
$\log X_T$		−.493[a]	−.371[a]	−.285[a]	−.266[a]	−.780[a]	−.292[a]
		(.029)	(.046)	(.043)	(.050)	(.057)	(.044)
T		−.010[a]					
		(.001)					
$\log Y_t$	−.472[a]		−.291[a]				−.052
	(.023)		(.026)				(.065)
$\log Z_T$				−.530[a]	−.524[a]		−.444[a]
				(.039)	(.043)		(.113)
Estimator	OLS	OLS	OLS	OLS	EGLS	OLS	OLS
Degrees of freedom	38	36	36	36	35	37	35
$\bar{R}^2$	.917	.981	.969	.978	.961	.868	.978
Durbin-Watson	1.113[b]	0.908[b]	0.847[b]	1.303[c]	1.485[d]	0.067[b]	1.263[c]

Note: Numbers in parentheses are standard errors.

[a]Coefficients are significantly different from zero at the 1 percent confidence level.

[b]The Durbin-Watson statistic does not exceed the lower bound at the 1 percent confidence level.

[c]The Durbin-Watson statistic exceeds the lower bound but not the upper bound at the 1 percent confidence level.

[d]The Durbin-Watson statistic exceeds the upper bound at the 1 percent confidence level.

despite the strong indications of economic and statistical significance. The result reported in column 1 of table 4.1 reproduces the common problem: the Durbin-Watson statistic is too small to support the null hypothesis of no autocorrelation at the 1 percent confidence level. That is to say, the OLS estimator that led to the fitted learning curve is most likely biased, the meaning of which is that the classical formulation of the learning curve (1) may well be misspecified. Figure 4.3 plots the residuals from the regression of column 1 and makes the issue obvious. The pattern that emerges is clearly far from random. Even if the dip at the beginning is explained away by the changeover from the E designation to the F designation, the systematic deviation occurring throughout 1944 suggests that variables are missing from the regression. This is the problem Alchian (1963) encountered when he found that the learning curve was not able to predict labor hours reliably. The learning curve tells us an interesting story. But as an explanation of quantitative facts it stands on remarkably shaky ground.

4.4 Inside Plant No. 2

It is one thing to find a flaw in the classic learning-curve formulation, but it is quite another to find an alternative explanation for the dramatic decrease in the direct labor hours expended on each B-17. Several hypotheses are conceiv-

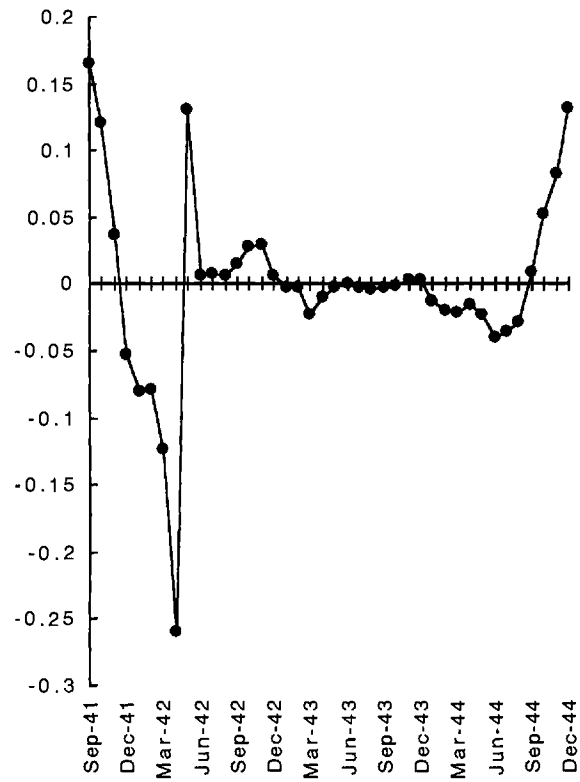

Fig. 4.3 The residuals

able. First, what happened is simply an example of scale economies. On the shop floor, in this interpretation, labor would have been divided more and more as production expanded from 5 airframes a month to 362 airframes a month. A second hypothesis might be that the learning-curve story was not tested properly by the calculations in column 1 of table 4.1 and in figure 4.3. The classic learning curve would be well specified if all the sources of Boeing's production experience were considered. A third possibility is that the quality of the airframes that were produced deteriorated over time or that the B-17 became, because of small design changes, a simpler product to build. This hypothesis amounts not to a claim that efficiency improved but rather to the claim that, as time passed, there was less work involved in building the B-17 airframes. Yet another possibility is that labor input might have improved. On this reading, the learning-by-doing hypothesis is still valid in fact, even though measurement is difficult. One more possibility, of course, is "none of the above." Something other than the division of labor was at work, but it is not quite learning by doing on the shop floor either. The text that follows scrutinizes these hypotheses based on the historical records of the B-17 production program.

4.4.1 Scale Economies

There is no denying that the decrease in the unit direct labor hours in the B-17 program was dramatic. But, then, so was the increase in output. Is it possible that the learning curve is yet another expression of the consequences of the transition from small- to large-scale operations? Answering this question requires a careful examination of the production processes as well as the changes made to them over time.

Boeing built the B-17 in the main building of Plant No. 2.[13] This huge square structure on a 66-acre site covered 37 acres under one roof and boasted a total floor space of 42 acres with balconies. The building was erected with utmost flexibility in mind.[14] Overhead cranes and underground utility tunnels permitted just about any layout configuration. In practice, work in progress moved from the west end of the building, where machine shops were located, toward final assembly on the east end just off the airfield. Between the two production areas was the enormous expanse of the subassembly area.

The subassembly area was divided into many rectangular sections of various sizes. These sections were bordered by a clear boundary because each was filled tightly with only one kind of airframe segment—inboard wing, for example—and adjacent sections were filled with completely different airframe segments. Figure 4.4 shows the inboard wing section (front) as well as the forward fuselage section (back). Between are several completed fuselages heading for final assembly. Figure 4.5 is a close-up view of the forward fuselage section. The production areas, proceeding from parts fabrication to subassembly to final assembly, were sandwiched by the storage areas that occupied the entire north and south sides of the building. The storage areas received shipments from subcontractors and suppliers, and in turn fed the production areas with the parts and materials they needed.

Boeing's production method featured a combination of stationary subassembly and short multiline final assembly. The idea was to minimize the time work in progress spent in the final assembly stage, because once the fuselage and the wings were joined, the airframe wasted space on the shop floor and unnecessarily increased the time workers spent walking back and forth. Thus, Boeing chose to break down the B-17's airframe production into roughly fifty subassemblies upon the arrival of the E designation. These subassemblies were neatly jammed into sections of their own in the subassembly area and completed there as independent units by moving crews while stationary in a holding jig. When a subassembly piece was ready to move on, it was picked up by

13. *Aviation* (July 1943) describes this building and the production method adopted therein.

14. When Plant No. 2 was erected, the company faced profound uncertainties with regard to the product mix and production volume both during and after the war.

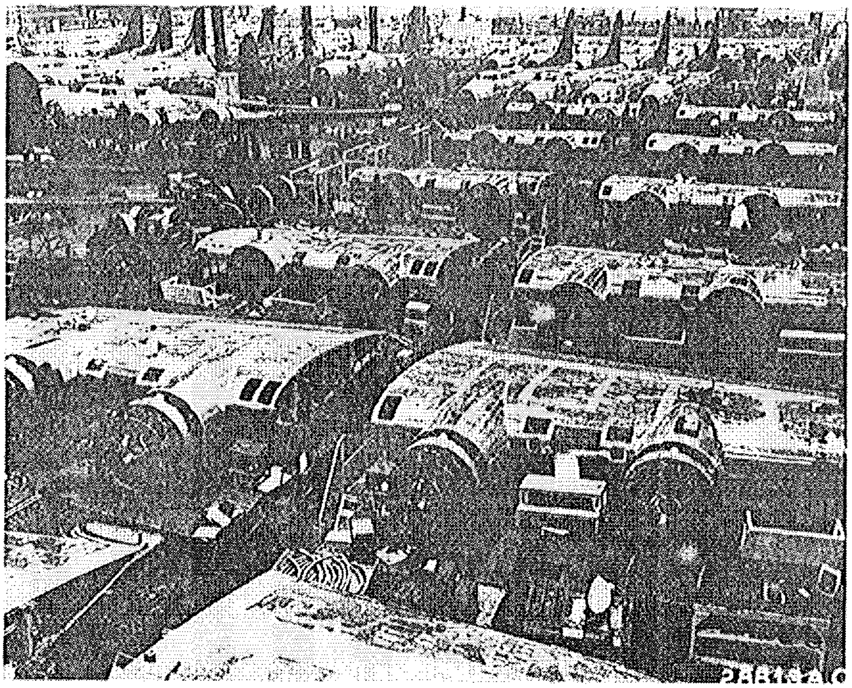

Fig. 4.4 B-17Es in Plant No. 2: inboard wing subassembly
Source: USAF Museum (Wright-Patterson AF Base).

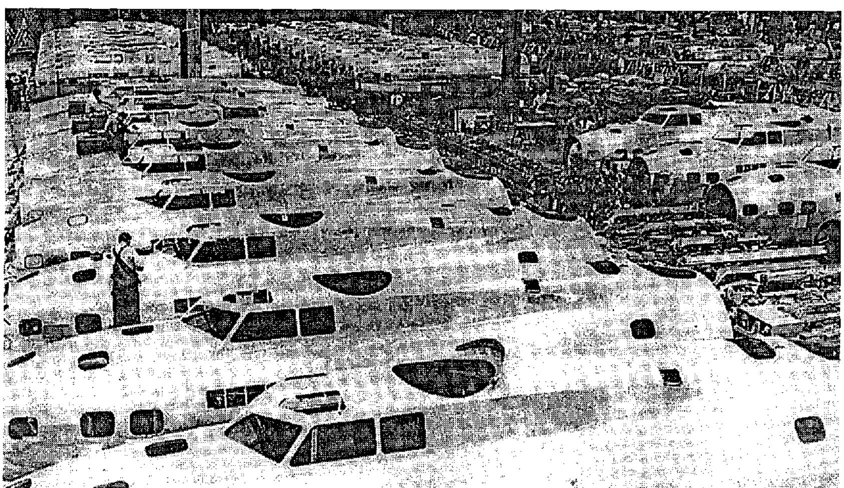

Fig. 4.5 B-17Es in Plant No. 2: forward fuselage subassembly
Source: Bowers (1976), 81.

an overhead crane and carried all the way to another section that would bolt it together with a few other subassemblies to form a major assembly segment—for example, the inboard wing segment comprising the body of the wing, flaps, engine nacelles, and deicers.[15] Major assemblies likewise joined one another on one of several final assembly lines, where the remaining work, such as attaching propellers, was divided among a few stations. Gigantic airplanes stood immediately one after another in this area, and moved every now and then on their own set of wheels for the first time. Figure 4.6 shows a final assembly line in Plant No. 2 (another is seen starting on the right-hand edge).

The huge plant building as well as the production method described above did not emerge overnight. Understanding the precise timing will prove to be important.[16] When Boeing started building the first B-17 (Model 299), it had only one manufacturing facility (Plant No. 1). In this plant, skilled workers fabricated parts with drop hammers, put together major segments of the airplane on wooden jigs, and installed assorted equipment on the airplane as it sat immobile in the center of the assembly building.[17] In 1935, in expectation of the coming of gigantic metal airplanes such as the B-17, Boeing acquired the land for Plant No. 2 one mile away from its original site. Thereafter, Plant No. 2's main building expanded through four projects. The first two of them, amounting to 9 percent of the floor space of the eventual main building, were carried out in 1936 and 1937. Figure 4.7 shows the very first B-17 (Model 299) being assembled in Plant No. 1 in 1935, and figure 4.8 shows B-17Bs being assembled in the brand-new Plant No. 2 in 1939.

With the coming of the B-17E, both the scale and the method of production changed significantly. The third expansion project commenced in May 1940, immediately following the French order for the DB-7 and President Roosevelt's call for 50,000 airplanes a year. The project added 38 percent of the floor space of the eventual main building, and occupancy began six months after the start of construction. In August 1940 Boeing established the Tooling Department for the first time, because approximately 75 percent of the tools were rendered obsolete by the design changes introduced to the B-17E. This group, staffed fully in one year, added hydraulic presses, steel jigs, and special alterations of general-purpose drilling and milling machines. In October 1940 Boeing obtained government financing and initiated the fourth expansion project. This last phase completed the remaining 53 percent of the main building to increase capacity from ten to sixty B-17s per month. In June 1941 another government-financing contract permitted Boeing to order additional machine

15. Beall (1945) offers an account of the design detail by the vice president of engineering at the time. Bowers (1976) contains the history of the airplane as well as a story told by its original designer.

16. The evolution of Plant No. 2 is reported in great detail in several issues of *Aero Digest,* including February 1937, January 1938, February 1938, November 1940, and October 1941.

17. Laudan (1936) offers an account by a factory superintendent as to how Boeing built the prototype model 299. See also Klemin (1940) and Bowers (1976) for informative photographs of Plant No. 2 when it was building the B-17B.

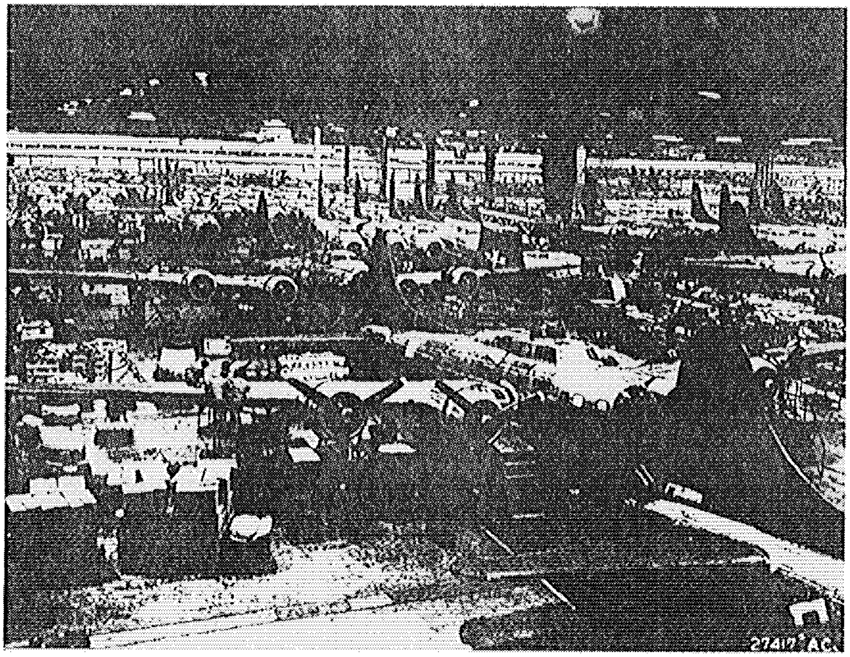

Fig. 4.6 B-17Es in Plant No. 2: final assembly
Source: USAF Museum (Wright-Patterson AF Base).

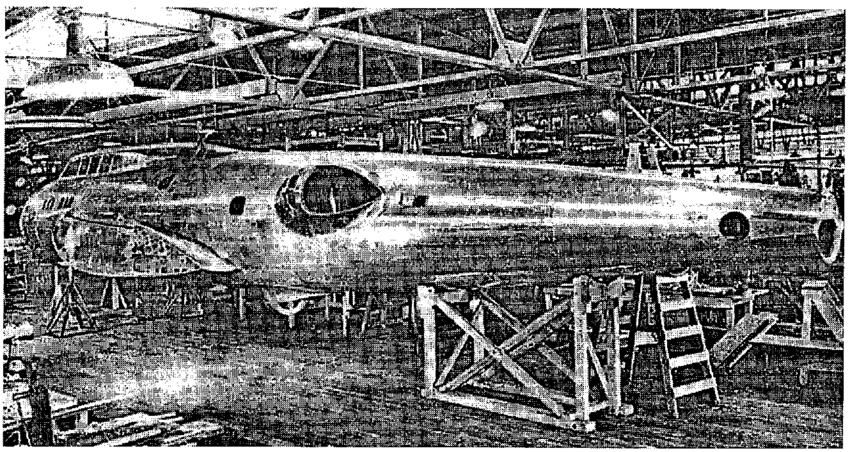

Fig. 4.7 Model 299 in Plant No. 1
Source: Bowers (1976), 44.

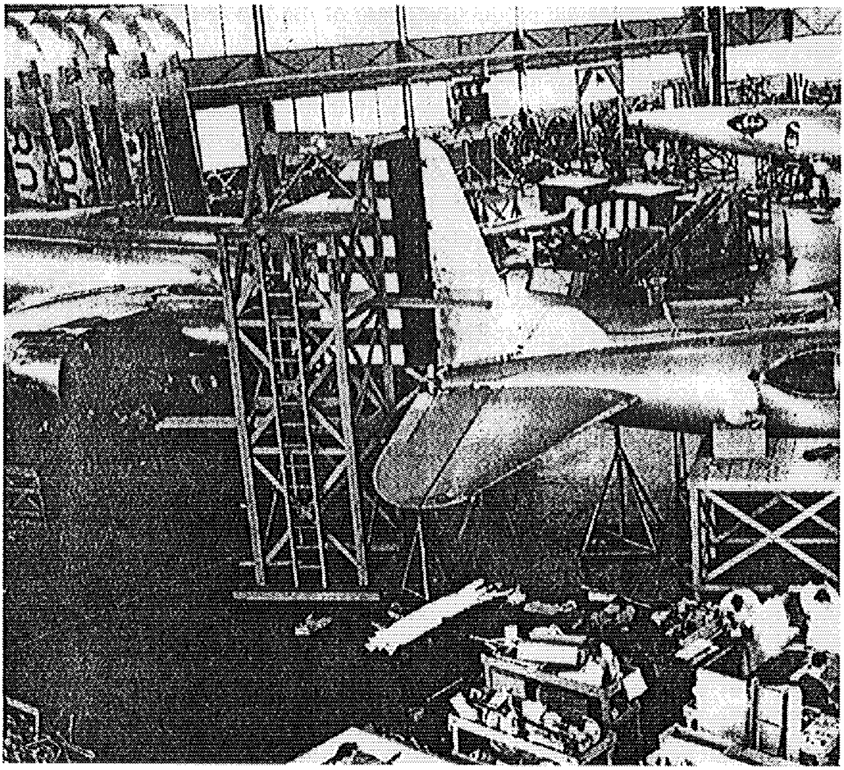

Fig. 4.8 B-17Bs in Plant No. 2
Source: Bowers (1976), 44.

tools and increase monthly capacity to seventy-five B-17s. Throughout these expansion projects, Boeing chose to extend its production philosophy that valued flexibility rather than reconfiguring the plant layout.

From available evidence, it seems that Boeing's resources for mass production were largely in place by the end of the B-17E run, that is, by May 1942 when the first B-17F was delivered. All told, Boeing added $17.4 million of fixed assets to its balance sheet from 1940 to 1945 for the war effort at Plant No. 2. Of these, 69 percent were in place by the end of 1941 and 96 percent by the following year. The Tooling Department had completed most of the required 70,000 dies and jigs in time for the beginning of the mass production of the B-17E. This included the oft-cited special-purpose equipment that Boeing credited for the productivity improvement. Major additions after May 1942 consisted of the expansion of warehouse space in the summer of 1942, the leasing of six feeder plants that increased plant space by 10 percent in the fall of 1943, and the construction of a cafeteria, an office building, and a wind tunnel in 1943. During the production phase of the B-17F and B-17G, there was no investment in productive capacity.

What does this all mean? The B-17's production version maintained a downward trend of the unit direct labor hours with neither notable capacity expansions nor changes in the production method. In fact, Boeing took the facility, equipment, and method that were designed to turn out 75 airframes a month, and built as many as 362 airframes at the peak of its monthly production. One may well argue, turning the logic of scale economies upside down, that large scale, as measured by the rate of output, is the result, and not the cause, of improved efficiency. Scale, as measured by the size of productive capacity, remained nearly constant, and is likewise unable to explain changes in the unit direct labor hours over a period as long as three years.[18]

What if scale is measured by the batch size? As figure 4.9 shows, the batch size shrank at the beginning with the introduction of the block production system, which was devised to cope with a flock of design changes on the basis of a relatively small standard batch size. The batch size then jumped from 100 airframes to 200 airframes with a period of struggling transition in between. In contrast to this stepwise movement of the batch size, the unit direct labor hours declined smoothly throughout much of these periods. Granted that the changes are by and large in the same direction, the patterns of change are too different to suggest that the batch size is the direct cause of improved efficiency. The reverse causal link—improved efficiency permitted the batch size to expand—seems, if anything, more plausible. To sum, no matter how scale is measured, scale economies cannot provide an adequate explanation for the dramatic efficiency improvement in the B-17 program.[19]

4.4.2 External Experience

The missing variable in the classic learning curve may well be experience external to the B-17 program. That is, the dramatic efficiency improvement is a learning effect after all. It is just that Boeing learned from sources other than its own experience of building B-17s. Does this line of reasoning hold water?

It appears that the answer is no. The Air Materiel Command (1946a, 6) remarks that "Boeing had had very little, if any, production experience prior to the B-17 program. They had produced airplanes, but never in quantity. The B-17 was their first real production program." In its quarter-century history prior to the war, Boeing built only some 2,100 airplanes, most of which had neither the metal construction nor the size of the B-17 (see *Aero Digest* July 1941). In contrast, it built more than three times as many B-17s: a grand total of 6,981 units. Boeing did assemble 240 Douglas-designed DB-7Bs for the French gov-

18. To be precise, productive capacity here refers to a concept of scale proposed by Alchian (1959): the contemplated volume of production. In the case of the B-17 at Plant No. 2, it remained basically constant at 75 airframes a month.

19. On the question of different notions of scale, see Alchian (1959) and Gold (1981).

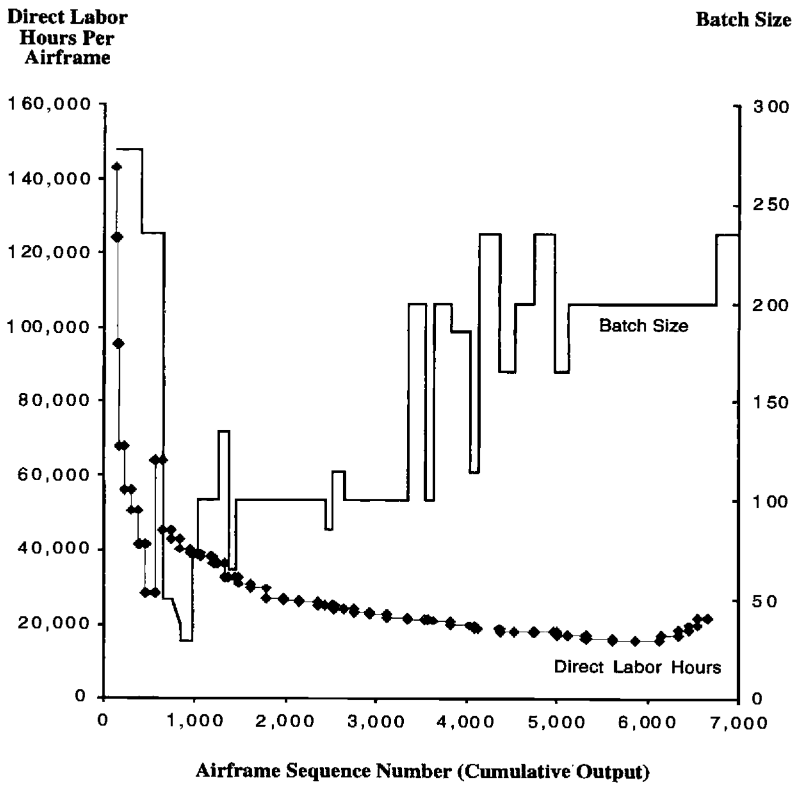

Fig. 4.9 The effect of batch size

ernment in 1940 at Plant No. 2, but even this experience pales in comparison with the B-17 program.

Not only did Boeing produce B-17s without any relevant previous experience, Plant No. 2 also did so without any relevant parallel experience. Boeing did develop another heavy bomber, the B-29, to replace the aging B-17 toward the end of the war, but Plant No. 2 actually built only three prototypes of that airplane. Mass production of the B-29 took place at Renton, Washington, and Wichita, Kansas, in the government-owned facilities, to which Plant No. 2 transferred a nucleus of personnel with a stack of engineering documents. Similarly, when Douglas and Vega joined Boeing in the production of the B-17F and B-17G in response to the solicitation from the government, and under license from Boeing, Plant No. 2 assisted these newcomers, and not vice versa.[20]

20. Chapter 20 of Holley (1964) describes the joint production effort, known as the BDV committee.

Plant No. 2 was always a mother plant rather than a recipient of know-how from external sources. If Boeing did learn from experience, the source of that experience must be found inside Plant No. 2 and with regard to the B-17.

4.4.3 Product Alteration

The B-17 built in 1944 might not have been the same B-17 built in 1941. If newer B-17s required less labor by design, the decrease in the unit direct labor hours observed in the B-17 program is not as dramatic as it first appears. Were there changes in the B-17 in ways that accommodate this line of argument?

The B-17 did undergo numerous engineering changes: 155 of them with the B-17E, 760 with the B-17F, and 634 with the B-17G. Few, however, were introduced to improve manufacturability or otherwise address concerns and suggestions from the shop floor. Boeing's engineering department was in fact overwhelmed by the requests from the battlefield that kept uncovering the B-17's weaknesses in every detail.[21] The most important feature of these changes was that the B-17 acquired more and more armament from batch to batch, and became, if anything, a more complex product to assemble. By the same token, the B-17's quality was always subjected to the toughest of any field tests one can imagine. Nevertheless, quality problems were never cited by any sources I have been able to uncover. On the contrary, the B-17 acquired a reputation of being the most rugged and well built of any heavy bomber as more and more crews returned alive from bombing missions in planes that were severely damaged by fierce enemy counterattacks (see Bowers 1976, chap. 9). To guarantee that this would be the case, the Army Air Forces accepted B-17s only after rigorous inspection by on-site representatives. It is inconceivable that the dramatic decline in the unit direct labor hours was caused by equally dramatic deterioration in the quality of the output, or by improvement in manufacturability.

4.4.4 Learning by Doing

Cumulative output is a proxy variable. It may have failed to represent the rising skill level of direct workers, but it is still possible that the behavior of the unit direct labor hours is explained by improvement in dexterity. Or is it?

Here is what happened with the workforce at Plant No. 2. Boeing initiated all-out hiring efforts in August 1941 as the first B-17Es neared final assembly. In just six months the number of direct workers increased from 9,972 to 21,083. However, this was the peak as far as the head count goes. After February 1942, turnover either outpaced or matched hiring, and the number of direct workers consequently fluctuated around 17,000 for the rest of the B-17 program. In fact, the chronic labor shortage was so severe that Boeing set up

21. The working-paper version of this paper (Mishina 1992, 19–21) offers additional data and formal analysis on the subject of engineering's contribution to efficiency improvement. The conclusion drawn is that the pattern of unit direct labor hours has little correlation with the hours logged by design engineers and/or toolmakers.

feeder plants in the summer of 1943 to tap into labor supplies outside the immediate Seattle area. Boeing also tried to make the best use of subcontractors starting with the B-17C, to mitigate the labor shortage. It did not take long to exhaust this source, however: the subcontracting ratio already reached 28 percent with the B-17E and never exceeded 33 percent thereafter. Just like the case of the fixed assets, the size of the workforce already approached its peak figure with the E designation.

Unlike the plant and equipment, the workforce underwent significant qualitative changes during the mass-production phase and its skill deteriorated considerably. The early variants of the B-17 were built by a group of skilled craftsmen who had learned the ins and outs of airframe production through trial and error. With the outbreak of the war, these men either enlisted or were promoted to supervisory positions, and Boeing had to tap into entirely new labor pools to staff Plant No. 2. "During 1941," the Air Materiel Command (1946a, 65) summarizes, "it could fairly be said that hiring specifications were strict, [but] as labor became scarcer the contractor was forced to adopt lower standards and take whatever labor was available." Given this reality, it is difficult to accept an argument that the quality of direct labor may have increased over time.

Moreover, whatever labor Boeing was able to employ did not stay with the company long enough to acquire new craft skills. For example, Boeing started hiring female workers for the first time in its history to cope with the chronic labor shortage.[22] Female employment, which was less than 1,000 in 1941, increased steadily and reached 16,000 by early 1944. In other words, Plant No. 2 attained its peak production as well as peak efficiency predominantly with green hands and *not* with the men who were brought into the plant by the massive hiring program of 1941. The heroic female workers—known generally as Rosie the Riveter—had had a factory job only for a year or two when Plant No. 2 recorded its best performance.[23] Unless labor skill is easily transferable, these facts undermine the learning-by-doing hypothesis that regards direct workers as the principal embodiment of experiential learning.[24]

4.4.5 Production System

It is clear by now that learning, in this case, went far beyond factor inputs. Simply stated, output and productivity did not peak until 1944 whereas the buildup of capital and labor leveled off by early 1942. There is also no apparent

22. See Froelich (1942) for general labor conditions of the industry.

23. The turnover rate was high throughout the B-17 program due partly to wage competition from the shipyards in the immediate vicinity. Absenteeism ranged from 7.2 percent (September) to 10.8 percent (December) in 1943, and from 5.5 percent (January) to 8.6 percent (October) in 1944.

24. The point is not to deny workers' ability to learn. Boeing's 1944 annual report credited workers, for example, by stating that in 1944 the Employee Suggestion System collected 12,493 entries, 2,380 (19 percent of which were awarded and put in use. The point is that Plant No. 2 exhibited a steady learning effect even when the faces of direct workers were constantly changing. Direct workers in this case collectively lacked the ability to accumulate learning.

indication of positive qualitative changes in capital and labor that were employed for the B-17F and B-17G. It is clear instead that learning at Plant No. 2 stretched its effective capacity well beyond the original plan—more than quadrupling, to be precise.

The only way in which this could have happened is through a rising velocity of work in progress that moved through the limited space of the main plant building. This point warrants elaboration, for it highlights the importance of the production system as distinct from factor inputs of production. Space limitation imposes an upper bound on the amount of work in progress (*WIP*) that can be stored on the shop floor. If system cycle time (*SCT*) is defined as the elapsed time between two successive units of output exiting the plant building, and throughput time (*TPT*) as the interval between the entry to and the exit from the plant building of a specific unit of output, the following relationship must hold true for a given unit of time.[25]

$$(2) \qquad \overline{WIP} \geq WIP = \frac{TPT}{SCT} = TPT \times (OUTPUT).$$

When monthly output increases, throughput time as measured in months must decrease accordingly once the plant exhausts all the floor space it can use. This is the precise meaning of the rising velocity. In Plant No. 2 the level of work-in-progress inventory actually declined steeply throughout 1943, and the weighted average throughput time dropped from 1.48 months in the last five months of 1942, down to 0.88 months in 1943, and further to 0.48 months in 1944.

The few accounts put forward in 1943 by the witnesses of wartime production suggest the linkage between the rising velocity and changes in the production system. One of them comes from the superintendent of tooling at Plant No. 2 (Bucey 1943). This manager assigned much of the credit for declining unit direct labor hours to the extensive tooling program, which explicitly focused on speedier production. Interestingly, the point he made was not so much about the time savings in machining: more important was the reduction of rework at assembly thanks to greater interchangeability of parts. Assembly in fact consumed about 80 percent of all direct labor hours, a substantial part of which dealt with rework.[26] Decrease in the amount of rework would certainly help airplanes to leave the plant building more rapidly and free up floor space for more units of work in progress at the same time.

A critical point here is the cause of greater interchangeability. There is no

25. *WIP* in equation (2) measures the number of airplanes in various stages of production, counting all of them equally.

26. Boeing's 1939 annual report blamed rework for losses it incurred on the B-17B. According to Bucey (1943, 221), "Incorrectly manufactured parts can result in abnormally high assembly costs which are difficult to segregate. If a part doesn't fit, the amount of rework on the job which must be done by the assembly shops is almost incalculable."

denying that the kind of equipment that arrived with the B-17E made a difference vis-à-vis the old days of low-volume production. Yet much had to do with procedures and simple devices. Bucey (1943) vividly illustrated an example in which a worker used a hand tool on his own discretion to keep production on schedule when regular equipment broke down, and consequently created tolerance problems downstream. Human errors and mistakes like this hurt interchangeability, despite good intentions, where there was, for example, no clear documentation specifying how abnormal situations should be handled under various circumstances. Plant No. 2 reduced these opportunities for human errors with production illustrations, templates, and revisions of tooling development procedures.[27] These initiatives were all an integral part of the production system.

Another account comes from executives of different heavy-bomber producers (Laddon 1943; Perelle 1943). They found that more than 70 percent of their throughput time went into handling and, due to backtracking, some parts traveled more than a mile between two stations that were only fifty feet apart. They concluded that the shop floor's crowded condition caused wastefulness, confusion, and inefficiency with increase in orders. Their solution was to streamline the process so that the right number of fabricated parts could reach the right place at the right time and the entire flow could be in a direct line to the last operation. They abolished the central finished-parts stockroom and made sure that the small stock bins carried only eight to ten days' supplies. This story amounts to a prefiguration of today's just-in-time (JIT) production.

Given Boeing's production method, which relied on overhead cranes for the handling of work in progress, implementation of JIT production must have been inevitable as soon as Plant No. 2 exhausted slack floor space. It was simply impossible to keep a larger number of bulky pieces of work in progress, such as forward fuselage, in transit, that is, hung in the air. Work in progress therefore could not leave one section and move on to the next until the destination section freed up a holding jig. In other words, production had to be pulled strictly from downstream sections. A plant tour report (*Aviation* July 1943, 310) thus stated: "Behind all this fluid activity is a perfect timing. If one division falls behind, it is as instantly apparent as an empty space in a line." It is not difficult to imagine the degree of coordination this plant required for production control.

A primary cause of the rising velocity at Plant No. 2 was the tighter implementation of JIT production. The Air Materiel Command (1946a, 36) pointed to one trend that persisted throughout the growth phase of the B-17 production program: "As the production schedules were increased, the degree of break-

27. Wright (1939) also emphasized similar managerial initiatives and cited Boeing for its use of templates to reduce errors and loss of parts, time, and material.

down [into subassemblies] was of necessity proportionately increased." In essence, Plant No. 2 divided the subassembly area into an ever larger number of smaller sections. As a result, the direct workers could work on a larger number of airframe segments of a given airplane at any given moment in the factory without interfering with one another. The change thus increased the intensity with which an airplane was assembled and, therefore, the velocity of production.

This gain did not come easily. More breakdown into finer subassemblies also meant less slack in each subassembly section and so less leeway for the smooth operations of the entire plant. Behind the rising velocity, the plant was increasingly vulnerable to any deviation from the way in which everything was planned to happen. In order to thrive under this taut environment, the production system must have undergone major changes. The procedures that the purchasing department developed to step up to the challenge of building the B-17E are good examples (*Aviation* June 1941). This group implemented methods to keep track of the status of all outside production parts, check vendors' work on site, and give suggestions to subcontractors. To administer these procedures, the staff expanded from six people at the beginning of the B-17E to a peak of 130. Similarly, production planning and control expanded from 200 people as of January 1939 to a peak of 2,960 in January 1945 (although the second figure contains the personnel for the B-29 and thus overstates the needs of the B-17 program). It is these core managers of the control departments at Plant No. 2 who learned what it took to increase the velocity of production.

4.4.6 Summary

The learning effect manifested itself in terms of declining direct labor hours. Either there was less work to do per airframe, or it must have taken less time to do a given amount of work. For the former to be true, there must have been product design changes that lent themselves to better manufacturability. In the B-17 program, design changes were initiated predominantly for higher product performance rather than improved manufacturability. Therefore, it must be the case that it somehow took less time to do a given amount of work. There are three possibilities corresponding to the different ways in which direct labor hours are typically spent—productive work time, nonproductive work time, and idle time. First, direct workers may have learned to do their real job faster and faster in the spirit of learning by doing or, alternatively, with the aid of capital investment. Second, direct workers may have spent less and less time performing nonproductive work such as material handling and inspection, and more and more time performing productive work. Third, direct workers may have spent less and less time waiting for parts, work pieces, and production instructions. The recent advance in operations management reveals how little of direct labor time went to productive work and how much went to the other two categories.[28] A close examination of the history of the B-17 program, a

28. See, for example, Imai (1986).

locus classicus of the learning-by-doing literature, strongly suggests that the measured learning effect stems primarily from the second and third possibilities. It is the system of production that embodies learning, not the direct workers themselves.

4.5 Ford Willow Run versus Boeing Seattle

It should be noted that the conclusion reached in the previous section is not unrelated to how Boeing chose to implement high-volume production. Specifically, Boeing stayed away from mass production pioneered by the Ford Motor Company. The peculiar features of Boeing's approach become crystal clear when Plant No. 2 is compared with a plant Ford operated in Willow Run, Michigan, in order to build the Consolidated B-24 heavy bomber and teach aircraft manufacturers the mass-production methods, equipment, and philosophies of the automobile industry.[29]

Boeing organized for flexibility. The Ford Willow Run plant showcased the hardware-centered approach to high-volume production. The plant covered 67 acres under one roof, and provided two 150-foot-wide areas more than 2,000 feet long. Ford broke down the B-24, which was similar to the B-17 in size, into approximately seventy subassemblies (40 percent more than Boeing did with the B-17), and laid down an assembly line to put them together progressively. The Willow Run plant also differed from Plant No. 2 in the use of permanent steel dies, elaborate fixtures, complex machine tools, and moving chain conveyors. Moreover, all of the jigs, fixtures, and main dies installed by Ford were of heavy, sturdy, long-lasting construction. In other words, Ford tried to achieve high volumes of output by the design of the process—a hallmark approach of mass production. It takes a lot of time and effort to complete tooling up front, but, once it is done, it does not take much thought to produce in high volumes, for the tooling itself embodies a pool of knowledge about how to execute production.

In contrast, Plant No. 2 chose the software-centered approach to high-volume production. Had all the work in progress been removed from the plant, it would have been an enormous empty box devoid of tangible structures suggesting how airplanes were built there. By the same token, Plant No. 2 was scalable in that it could adjust to a wide range of production rates without drastic changes in the operating efficiency. Willow Run, with its fixed production process, needed a certain number of people to run regardless of the production rate because the division of labor there created a predetermined number of positions to be staffed at all times.

Willow Run was highly efficient once it was up and running. However, it refused to run for an unexpectedly long time until minute technical details

29. Air Materiel Command (1946b), vii. The Willow Run plant was owned by the government, unlike Boeing's Plant No. 2.

were all sorted out. In fact, the war was over before the plant reached peak capacity. The efficiency of Willow Run was due mainly to scale economies—process design geared rigidly to a large scale of output from the outset. In this respect, it is analogous to Adam Smith's pin manufacturer that set up a process employing ten persons. What appears a learning process here is merely a period of adjustment—much like friction in physics—that is necessary before the process design reaches its potential. As soon as the potential is reached, however, there will be no further progress. Whether a plant is blessed with scale economies or learning economies is largely a question of the process design it chooses to implement at the outset (Zeitlin 1995).

4.6 Indices of Experience

If learning is embodied in the production system, how should the classical learning curve be modified? To answer this question, we must return to the regression. In the context of learning on the shop floor, it has been customary to consider experience somewhat narrowly as representing the history of production activities. To formalize this idea, let X_t stand for the output in month t. Alternative measures of experience as of month T are then expressed by different ways to sum up the raw data, $(X_1, X_2, \cdots, X_T)$. Three summary indices immediately suggest themselves: the elapsed time T, the cumulative output $Y_T = \sum_{t=1}^{T} X_t$, and the maximal proven capacity to date $Z_T = \max_{1 \le t \le T} X_t$.

T represents "learning by thinking." Although it is often argued that elapsed time would matter because of the external progress of technology (Fellner 1969), the duration and the surroundings of the B-17 program largely invalidate this interpretation. This variable must therefore stand for the viewpoint that the most scarce input to learning is the time to think. The choice of the time scale was made immaterial in the following analysis by entering this variable in the exponential form of e^T.

Y_T captures "learning by doing" or activity-based experience. This stock variable grows only with stimuli from production activities, but in doing so does not distinguish whether or not activities are simply repetitive. It could thus be associated with either direct labor skill improvement or accumulation of technical know-how.

Z_T in contrast represents "learning by stretching." This boundary variable grows only when the plant stretches its activity level to a new height. It is a good proxy for the production system in place. The plant needs to revamp its production system in order to stretch. Once the production system is revamped, however, it will stay put even when the output level goes back down. Unlike the cumulative output measuring *total* experience, Z_T stands for *new* experience, discriminating whether current production activities push the frontier of experience forward and disregarding any redundant experience.

The bulk of table 4.1 is designed to evaluate these alternative expressions of experience within the following class of model specifications:

$$\log l_T = \theta + \alpha \log k_T + \beta \log X_T + \delta \log E_T + \varepsilon_T, \tag{3}$$

where k_T is a capital-labor ratio, E_T an index of experience, θ a constant, and ε_T a random disturbance term. This formulation is equivalent, up to the disturbance, to the standard Cobb-Douglas production function:

$$X = AK^{\frac{-\alpha}{1+\beta}} L^{\frac{1+\alpha}{1+\beta}} E^{\frac{-\delta}{1+\beta}}, \tag{4}$$

where A is a constant, $L_T = l_T X_T$ is the total direct labor hours, $K_T = k_T L_T$ is the productive capital stock available in month T, and the last term containing an experience variable works as a shifter of the production function. The appendix discusses the capital data in detail.[30]

Observers of wartime production often attributed the dramatic reduction of unit direct labor hours to the adoption of mass-production techniques.[31] The analysis here controls for this consideration with two variables—the rate of output X_T (Viner 1931) and the capital-labor ratio k_T—while attributing the remainder of the labor-hours reduction to experiential learning.

Rapping (1965) applied model (4) to the Liberty Ship data during World War II. He concluded that the learning effect was related to the cumulative output more than to the elapsed time because the latter's coefficient became insignificant in the presence of the former variable. Argote, Beckman, and Epple (1990) used the same data set and the same formulation with another experience variable of the form $\sum_{t=1}^{T} \lambda^{T-t} X_t$, that is, the cumulative output discounted at a constant rate. They found that this variable, or knowledge after forgetting, explained the learning effect even better than the simple cumulative output. Their result on the depreciation rate λ suggested that only 3.2 percent of the knowledge stock survived one year later and labor turnover had little to do with this high rate of forgetting. These findings are no doubt interesting but demand an explanation as to who knows what in the first place and why a learning agent can forget the content of learning so fast. Answering these questions is difficult within the Liberty Ship data because they contain many independent shipyards.

The analysis of the B-17 data reported in table 4.1 tells a clear-cut story about Plant No. 2, a plant that had only one product. Columns 2 through 4 present the result of employing e^T, Y_T, and Z_T, respectively in place of E_T in equation (3). The coefficients are all statistically significant and the fit is always excellent. They also exhibit scale economies and the effect of capital-labor substitution as expected. In spite of these desired properties, columns 2 and 3 suffer profoundly from serial correlation of the residuals. The character-

30. This study actually derived k_T as K_T / L_T. The denominator is not the head count of direct workers because the Air Materiel Command (1946a) stopped reporting this data as soon as the B-29 conversion project made it unclear how many workers were engaged in the B-17 program on a full-time basis.

31. See Middleton (1945) and Simonson (1960) for aircraft production and Searle (1945) for shipbuilding.

istic combination of a high $\bar{R}^2$ and a low Durbin-Watson statistic suggests that these two models capitalize on chance to fit the data. Their residuals indeed show a clear pattern: a model incorporating either e^T or Y_T systematically underestimates the unit direct labor hours whenever they cease to decline. The problem is that both e^T and Y_T consistently grow and, therefore, are unable to explain any reverse movement of the dependent variable. The B-17 data aggravate this problem because the unit direct labor hours reversed the downward trend during the cutback phase of the production program.

In contrast, the Z_T measure in column 4 escapes the problem of serial correlation. First, this model has a high enough Durbin-Watson statistic to exceed the lower bound at the conventional 1 percent confidence level. Test for autocorrelation thus presents no positive sign of missing variables. Second, even if serial correlation does exist, its consequence is minimal for the result in column 4. Column 5 replaces OLS with EGLS (estimated generalized least squares) adopting the two-step Cochrane-Orcutt method.[32] The result of this procedure is parameter estimates extremely close to those of column 4.

The reason only Z_T escapes serial correlation is more than a statistical accident. In other data that consist only of the expansion phase, it would be tricky to separate the effect of the scale variable and alternative experience variables.[33] In the B-17 data the presence of the cutback phase breaks this collinearity. Figure 4.2 shows that the unit direct labor hours at a given rate of output differed between before and after the peak of production. It is this gap that an index of experience ought to explain. The extremely low Durbin-Watson statistic of column 6 in table 4.1 attests to the existence of a missing variable aside from k_T and X_T. Both e^T and Y_T fail to fill the gap because their growth is too regular. From a technical viewpoint, Z_T mitigates this problem because it grows selectively. It too is irreversible, but it at least stays constant during the cutback phase. As a result, column 4 leaves only random residuals and no indication of further missing variables.

The evidence from Boeing's B-17 production program thus offers strong support to the hypothesis of learning by new experiences.[34] The source of learning then is the new experience that is inherent in the challenges of scaling up effective capacity. The alternative hypothesis of learning by doing contradicts the data at least in one respect because they suggest that no learning took place during the cutback phase of the B-17 program.[35] In the last column of

32. The first-step residuals yielded a correlation coefficient of $\hat{\rho}$ = .307.

33. In the B-17 data the correlation coefficient with the rate of output X_T for the first thirty-one months of expansion is .608 for e^T, .966 for Y_T, and .996 for Z_T.

34. This empirical finding substantiates widespread intuition and Arrow (1962), in reviewing works of psychologists, alluded to new stimuli as the engine of steadily increasing performance; Dutton and Thomas (1984) similarly referred to the learning opportunities that scale-up brings about.

35. Of course, it is conceivable that confusion associated with the B-29 conversion washed out the effect of learning that did occur even during the cutback phase. Based on the available evidence discussed in the previous section, the present analysis takes a position that at least during 1944

table 4.1, Z_T indeed nullifies the effect of cumulative output Y_T. As in Argote, Beckman, and Epple (1990) a high depreciation rate would technically relax the rigidity of the cumulative output, but would soon run into the difficulties of explaining constant rapid forgetting.

4.7 A Model of Scale-up Economies

This section integrates all the findings from Boeing's B-17 production while attempting generalization beyond a specific historical case. It first converts the empirical formulation of the last section into a schematic model describing the dynamic behavior of manufacturing cost. It then lays out the model's underpinnings by linking the agent, content, and source of learning explicitly to the production system and the operating know-how embodied therein. The section finally discusses the model's implications briefly.

4.7.1 The Model

The quantitative analysis of the B-17 program gave rise to the following formulation in section 4.6 (table 4.1, column 5): $l = \phi k^{\alpha} X^{\beta} Z^{\delta}$. This formulation conceptually translates into a dynamic cost function of the form

(5) $$C = C(X, Z) \quad \text{for} \quad \forall X \leq Z.$$

The first step is to extend the unit direct labor hours to the total unit cost on the left-hand side and generalize the functional form to accommodate this extension. The rationale is that the unit direct labor hours often signal the efficiency of entire operations. Such was clearly the case in Plant No. 2, where the rising velocity of production was the direct cause of the reduction in the unit direct labor hours.

The second step concerns the right-hand-side variables. Section 4.6 singled out three determinants of the unit direct labor hours: the capital-labor ration k (factor substitution effect), the rate of output X (scale economies), and the proven effective capacity Z (learning effect). Of these, the last two variables explain the bulk of the 89.2 percent labor savings that Plant No. 2 achieved between September 1941 and August 1944.[36] In contrast, the capital-labor ratio is statistically significant but economically unimportant because it did not fluctuate much. Capital and labor tended to grow together rather than one substituting the other. The coefficient of variation is 53.2 for X, 57.6 for Z, and only 33.7 for k. The last figure even drops to 16.1 without the first four months of 1941 when workforce expansion was still catching up with plant expansion.

the increase in the unit direct labor hours reflects negative economies of scale due to the cutback itself.

36. During this period, Z increased more than 17 times, which, given the estimated coefficient, would trigger 77.5 percent reduction in the unit direct labor hours all by itself. Likewise, X recorded a 52-fold increase, which alone would cause 65.0 percent reduction. These two effects combined are more than sufficient to explain the actual labor savings.

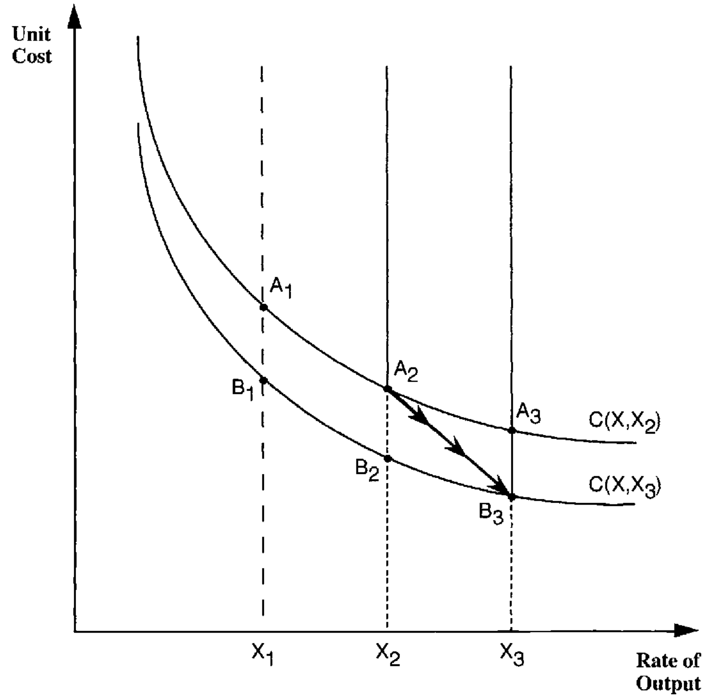

Fig. 4.10 Dynamic cost function

The factor substitution effect is therefore omitted from the dynamic cost function.

The cost function (5) is dynamic partly because it departs from the aggregation approach of the past. The classical learning curve aggregates all the determinants of the unit cost in one variable: the cumulative output *Y*. It was an antithesis to the traditional scale economies where the rate of output *X* assumed the role of a sole explanatory variable. The dynamic cost function, however, acknowledges the presence of both reversible and irreversible effects on the unit cost. The two variables, *X* and *Z*, that it incorporates are measurable in an identical quantitative unit and capture the dynamic behavior of manufacturing cost in a simple diagram.

Figure 4.10 shows the workings of the dynamic cost function. First, let's assume that the plant has experienced the output rate of up to $Z = X_2$. The curve $C(X, X_2)$ depicts the reversible effect, describing the unit cost as a function of the rate of output X. As the plant moves back from X_2 to X_1, so does its cost position from A_2 to A_1. By the same token, the cost declines from A_1 to A_2 as the plant increases output from X_1 to X_2 due to conventional scale economies. The location of X_1 is arbitrary so long as it lies to the left of X_2. The extension of the curve $C(X, X_2)$ to the right of X_2 is illusory since the plant has never operated in this domain. The figure empirically postulates that the curve (5) is downward sloping, that is,

$$\frac{\partial}{\partial X}C(X,\ Z) = C_X \leq 0 \quad \text{for} \quad \forall X \leq Z, \tag{6}$$

based on the finding that the coefficient of X, or β in model (3), is unambiguously negative.

Now, what happens when this plant scales up from X_2 to X_3? According to the dynamic cost function, the plant's cost position will shift from A_2 to B_3, of which the vertical gap between A_2 and A_3 is due to the reversible effect and that between A_3 and B_3 due to the irreversible shift of the curve $C(X, X_2)$ down to $C(X, X_3)$. The curve connecting B_1 and B_3 corresponds to the new reality that the plant has pushed its frontier from the vertical line $A_2 - B_2$ to $A_3 - B_3$ and irreversibly experienced the rate of output as high as X_3. Once this shift occurs, the cost position reverts to B_1, as opposed to A_1, even when the production is scaled back to X_1. The dynamic cost function thus postulates that

$$\frac{\partial}{\partial Z}C(X,\ Z) = C_Z \leq 0 \quad \text{for} \quad \forall X \leq Z. \tag{7}$$

The basis for (7) is again the empirical result demonstrating that the coefficient of Z, or δ in model (3), is unambiguously negative. It is this downward shift of the dynamic cost function over the X axis that represents learning, or more specifically scale-up economies.[37]

4.7.2 Discussion

There is no denying that the model of scale-up economies stands on only one study of one plant. More studies are undoubtedly needed to claim the model's applicability elsewhere. It is nonetheless useful to explore the implications of the new model since its merit also depends on the credibility of the story it tells.

One immediate payoff of the new model is its ability to resolve a controversy over the learning curve: whether the learning curve would remain in effect forever or the unit cost would cease to decline at some point. Explanations abound for individual cases where the unit cost did level off (Asher 1956; Baloff 1966; Conway and Schultz 1959). However, there have been no theoretical predictions as to where and when a plateau might appear. With the proposed model, plateauing is a natural consequence for the plants that stop scaling up. If they further cut back production and start operating under longer

37. The dynamic cost function suggests a new distinction between short run and long run. In the neoclassical theory of production, this distinction hinges upon whether or not a time period is long enough to permit changes in the plant scale while holding the stock of technical knowledge constant. Instead, it may be more fruitful to consider long run as a time period long enough to permit changes in the effective capacity Z.

system cycle times, the model would predict "toe-up" (Reguero 1957) in which the unit cost begins to climb as it did in Boeing's B-17 data.

The proposed model also offers implications for plant management. If experience is measured by the cumulative output as in the classical learning curve, every bit of production counts equally toward cost reduction and, therefore, there is not much the plant can do except to keep producing. With the new model, there is no learning where there is no challenge. Simply repeating the same production activities would not contribute to cost reduction autonomously because production counts only at the margin of experience. In order to learn, the plant must overextend itself beyond current effective capacity. Even though effective capacity may not be a control variable in the short run, scale-up with minimal investment might focus a plant on a set of activities that propels all functional units toward higher efficiency. It remains to be seen how important the kind of resource constraints that existed in Plant No. 2, especially limited plant space, really is for the learning effect to occur and continue.

The new model raises a subtle question of optimal scaling-up strategy. If $C_{ZZ} \geq 0$ holds as a finer property of the dynamic cost function, it would favor incremental scale-up whereby efforts are devoted to cycle-time reduction whenever possible and however small each gain may be. Otherwise, surpassing a threshold scale becomes a foremost priority. Inference of this property is not straightforward since most functional forms, including the Cobb-Douglas, impose convexity. One way to bring the B-17 data to bear on the question of optimal scale-up strategy is to expand the term log Z to the second order where the coefficient of Z^2 must be negative if C_{ZZ} is ever to fall below zero. The result shows a small positive coefficient that is not statistically different from zero. Combined with the lack of clear patterns in the residuals of the Cobb-Douglas model, the B-17 data seem to support global superiority of the incremental scale-up strategy.

The model also poses a crucial question about the management of know-how. The best scenario calls for growth that would keep X at rising Z and thereby reap economies of scale and scale-up simultaneously. If the unit of analysis for which this model holds true remains at the plant level, such growth should not scatter over many different plants. Other things being equal, a firm should rather develop a centralized manufacturing complex that would retain all the know-how. A different conclusion will result if it is possible to share know-how effectively within a network of plants. Unfortunately, the present study of one plant is not designed to address this question concerning the organizational boundary of know-how. It only suggests the variables to measure in future research.

Another strategic implication revolves around the role of incumbency. If cumulative output is the adequate measure of experience, the learning effect should give rise to strong first-mover's advantage in terms of manufacturing cost (Spence 1981). The upshot is a high entry barrier and concentrated industry structure, which are strangely missing from certain industries that are believed to exhibit the learning effect. In the proposed model, it is not the incumbency per se that matters. In this regard, the model agrees with the findings of Argote, Beckman, and Epple (1990) in spite of the differences in its specification.

4.8 Conclusion

This essay examines a historical case that resembles a controlled laboratory experiment. Under special circumstances of wartime production, one plant manufactured one product for one customer who kept detailed records of production activities to make sure that weapon manufacturers did not profit from the war. The case further contained a cutback phase where scale shrank clearly but experience did not. This feature allowed the essay to isolate these two critical variables that are highly collinear in most data. From a methodological standpoint, the essay departs from previous studies that used minute differences in the goodness of fit to guide the process of model selection. It instead relies on serial correlation as well as nonquantitative case information. The result is a clear rejection of the learning-by-doing hypothesis that holds direct workers or engineers as the learning agent. The following points summarize the emerging, alternative conception of learning:

1. The source of learning is *new* experiences that scaling-up of effective capacity entails. In Boeing's Plant No. 2, learning did not seem to occur when production was cut back even though production itself continued at a smaller scale. In other words, "quality" of experience mattered. Doing alone, without any regard to the redundancy of experience, did not give rise to learning.

2. Scale-up triggers *system* changes. Changes that took place in Plant No. 2 were subtle, and concentrated in the area of management of operations: how to manage a smooth flow of work in progress from vendors to the plant and inside the plant itself despite space constraints and despite a host of problems that could occur unpredictably. Thus, the content of learning is operating know-how, which makes up the production system.

3. The agent of learning is the core managers of control functions in the plant, that is, those who *coordinate* various aspects of the plant operations to ensure that work in progress flows smoothly without interrupting events so the shop manager can concentrate on his or her job of meeting production schedules while supervising the direct workers. In Plant No. 2, departments such as production control grew most rapidly as the plant exhibited learning effects.

4. During the four years Boeing produced the B-17s in high volumes, the unit direct labor hours declined from roughly seventy-one worker-years to eight worker-years. The magnitude involved here is clearly too large to be explained by skill improvement. In Plant No. 2 the bulk of labor savings appeared to originate from the hours in which direct skill was not being applied in the first place. The key was instead throughput-time reduction and the operating know-how that enabled it.

5. The hardware of production has little to do with learning in airframe fabrication and assembly. In Plant No. 2 the learning effect took place long after capital investment was suspended. The same goes for product and process engineering. These elements may be necessary for production, but not sufficient for the observed cost dynamics. Factor substitution effect was economically unimportant, although scale economies prevailed along with scale-up economies.

Appendix

This study constructed the capital data through three steps: (1) determining the base capital that existed in Plant No. 2 prior to the expansion projects undertaken for the B-17 program, (2) adding to the base the capital expended for the expansion projects on a monthly basis, and (3) adjusting the resulting monthly data for subcontracting as well as the conversion to the B-29. What follows explains each step in some detail.

Base

The base line represents the capital that had accumulated in Plant No. 2 since land was acquired for this new site in 1935, until the beginning of 1940. It excludes Plant No. 1 and a subsidiary facility in Wichita, Kansas. The base was estimated at $1,156,159 from Boeing's annual reports through the following calculation:

$3,230,070	Property and equipment at cost as of 31 December 1939 for Boeing Airplane Company
(1,890,207)	Property and equipment at cost as of 31 December 1934 for Boeing Airplane Company
(371,304)	Property and equipment at cost as of 31 December 1939 for Stearman Aircraft Division
187,600)	Property and equipment at cost as of 31 December 1934 for Stearman Aircraft Company
$1,156,159	

Additions

Four expansion projects involved the main building of Plant No. 2 and increased its productive capacity. The total amount of investment was allocated equally from the month in which occupancy started to the month in which the project was completed. The construction period, typically six months, was ignored because capacity was unavailable for production. Table 4A.1, lists the projects. The Air Materiel Command (1946a) contains more detailed information.

Table 4A.1 Expansion Projects for Plant No. 2

Project	Investment ($)	Occupancy	Completion
Private	2,107,218	November 1940	July 1941
EPF W535 ac-16424	7,777,587	March 1941	April 1942
EPF W535 ac-196	3,191,580	November 1941	December 1941
EPF W535 ac-26185	1,238,662	June 1942	September 1942

Table 4A.2 Feeder Plants

Plant	Completion of Assembly	Total Square Feet
681	October 1943	38,700
682	November 1943	47,100
683	November 1943	49,630
684	November 1943	37,086
685	December 1943	33,050
686	December 1943	51,000
687	October 1944	33,300

Boeing also added seven feeder plants in 1943 and 1944 as in table 4A.2. These facilities were added to the monthly capital data at $3.50 per square foot, which was typical for Boeing's own investment, in the month when they recorded the first line-off.

Adjustment

To make the capital data comparable to the direct labor hours data, the resulting monthly capital data were divided by one minus the subcontracting ratio to adjust for subcontracting. The subcontracting ratio was 28 percent in 1941 and 1942, 29 percent in 1943, and 32.6 percent in 1944. The data were then scaled down to reflect the conversion to the B-29. The delivery of the B-29 from Renton began in January 1944 and continued throughout the year at a monthly rate between two airplanes and thirty-five airplanes. Hershey (1944) describes the manner in which Plant No. 2 was converted for this purpose from April 1944 to March 1945. Based on this information, the capital data were linearly reduced beginning with April 1944 so that they reach zero in May 1945 when Plant No. 2 was no longer engaged in the B-17 program.

References

Aero Digest. 1937. Specially Planned Modern Building for Final Assembly. (February): 32–34.

———. 1938a. Equipment and Procedure for Constructing Four-Engined Airplanes. (January): 17–19.
———. 1938b. Monorail Crane Equipment at Boeing's New Assembly Plant. (February): 38–39.
———. 1940. Boeing-Stearman. (November): 40–41.
———. 1941a. More Factory Areas Dedicated to Aircraft Production. (October): 60–66, 392.
———. 1941b. The 25th Anniversary of Boeing Aircraft Co. (July): 73–78.
Air Materiel Command. 1946a. B-17 Production and Construction Analysis: Boeing Aircraft Company, Seattle, Washington. May. Typescript.
———. 1946b. B-24 Construction and Production Analysis: Ford Motor Company, Willow Run Bomber Plant, Ypsilanti, Michigan. August. Typescript.
Alchian, A. 1959. Costs and Outputs. In *The Allocation of Economic Resources: Essays in Honor of B. F. Haley*, ed. M. Abramovitz, 23–40. Stanford, CA: Stanford University Press.
———. 1963. Reliability of Progress Curves in Airframe Production. *Econometrica* 31, no. 4:679–93.
Andress, F. 1954. The Learning Curve as a Production Tool. *Harvard Business Review* 32, no. 1:87–97.
Argote, L., S. L. Beckman, and D. Epple. 1990. The Persistence and Transfer of Learning in Industrial Settings. *Management Science* 36, no. 2:140–54.
Arrow, K. J. 1962. The Economic Implications of Learning by Doing. *Review of Economic Studies* 29:155–73.
Asher, H. 1956. *Cost-Quantity Relationships in the Airframe Industry (Project Rand R-291)*. Santa Monica, CA: Rand.
Aviation. 1941. 248 Factories Build the Flying Fortress. (June): 74–75, 176, 186.
———. 1943. Fortresses by Boeing. (July): 124–29, 309–13.
Baloff, N. 1966. Startups in Machine-Intensive Production Systems. *Journal of Industrial Engineering* 17, no. 1:25–32.
Beall, W. E. 1945. Design Analysis of the Boeing B-17 Flying Fortress. *Aviation* (January): 121–44.
Boston Consulting Group. 1972. Perspectives on Experience. Boston. Leaflet.
Bowers, P. M. 1976. *Fortress in the Sky*. Granada Hills, CA: Sentry Books.
Bucey, B. K. 1943. Good Tooling Simplifies Production of Flying Fortresses. *Aviation* (January): 107–11, 221.
Conway, R. W., and A. Schultz, Jr. 1959. The Manufacturing Progress Function. *Journal of Industrial Engineering* 10, no. 1:39–54.
Craven, W. F., and J. L. Cate. 1955. *The Army Air Forces in World War II*. Vol. 6, *Men and Planes*. Chicago: University of Chicago Press.
Davis, L. 1984. *B-17 in Action*. Carrollton, TX: Squadron/Signal.
Dutton, J. M., and A. Thomas. 1984. Treating Progress Functions as a Managerial Opportunity. *Academy of Management Review* 9, no. 2:235–47.
Fellner, W. 1969. Specific Interpretations of Learning by Doing. *Journal of Economic Theory* 1:119–40.
Froelich, M. H. 1942. Women in War Work. *Aero Digest* (September): 132–36, 258–64, 298.
Gold, B. 1981. Changing Perspectives on Size, Scale, and Returns: An Interpretive Survey. *Journal of Economic Literature* 19:5–33.
Hershey, S. 1944. Boeing Converts Seattle Plant from B-17 to B-29 Production. *Aviation News* (4 December): 35–37.
Hirsch, W. Z. 1952. Manufacturing Progress Functions. *Review of Economics and Statistics* 34, no. 2:143–55.
Hirschmann, W. 1964. Profit from the Learning Curve. *Harvard Business Review* 42:125–39.

Holley, I. B. 1964. *Buying Aircraft: Material Procurement for the Army Air Forces.* Washington, DC: Department of the Army.
Imai, M. 1986. *Kaizen: The Key to Japan's Competitive Success.* New York: McGraw-Hill.
Klemin, A. 1940. Planning to Assure National Production. *Aero Digest* (May): 42–46, 179.
Laddon, I. M. 1943. Reduction of Man-Hours in Aircraft Production. *Aviation* (May): 170–73, 356–60.
Laudan, F. P. 1936. Factory Procedure in the Fabrication of All-Metal Aircraft. *Aero Digest* (January): 26–29.
Levy, F. K. 1965. Adaptation in the Production Process. *Management Science* 11, no. 6: B136–54.
Middleton, K. A. 1945. Wartime Productivity Changes in the Airframe Industry. *Monthly Labor Review* 61, no. 2: 215–25.
Mishina, K. 1992. Learning by New Experiences. Working Paper 92–084. Harvard Business School.
Perelle, C. W. 1943. Present-Day Manufacturing Problems of the Aircraft Industry. *Aero Digest* (May): 158, 340–47.
Rae, J. B. 1968. *Climb to Greatness: The American Aircraft Industry, 1920–1960.* Cambridge: MIT Press.
Rapping, L. 1965. Learning and World War II Production Functions. *Review of Economics and Statistics* 47:81–86.
Reguero, M. A. 1957. *An Economic Study of the Military Airframe Industry.* Department of the Air Force.
Searle, A. D. 1945. Productivity Changes in Selected Wartime Shipbuilding Programs. *Monthly Labor Review* 61, no. 6:1132–47.
Simonson, G. R. 1960. The Demand for Aircraft and the Aircraft Industry, 1907–1958. *Journal of Economic History* 20, no. 3:361–82.
Smith, A. [1776] 1976. *An Inquiry into the Nature and Causes of the Wealth of Nations.* Ed. Edwin Cannan. Chicago: University of Chicago Press.
Spence, A. M. 1981. The Learning Curve and Competition. *Bell Journal of Economics* 12:49–70.
Viner, J. 1931. Cost Curves and Supply Curves. *Zeitschrift für Nationalökonomie* 3: 23–46.
Wright, T. P. 1936. Factors Affecting the Cost of Airplanes. *Journal of the Aeronautical Sciences* 3, no. 4:122–28.
———. 1939. American Methods of Aircraft Production. *Journal of the Royal Aeronautical Society,* 131–52.
Yelle, L. E. 1979. The Learning Curve: Historical Review and Comprehensive Survey. *Decision Sciences* 10:302–28.
Zeitlin, J. 1995. Flexibility and Mass Production at War: Aircraft Manufacture in Britain, the United States, and Germany, 1939–1945. *Technology and Culture* 36:46–79.

Comment Ross Thomson

Ongoing productivity growth is not only a critical feature of capitalist development, it also forms a vexing problem for economic analysis, which often con-

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ceives technical change as something that happens to firms, not by them. Insightfully taking up this problem, Kazuhiro Mishina forwards both a striking example of productivity growth and a plausible explanation of how learning within the firm led to this growth.

Mishina examines the Boeing plant that manufactured the B-17 bomber, the so-called Flying Fortress, during World War II. Productivity growth was remarkable; labor time per airframe in 1944 had fallen to about one-tenth of that three years earlier. Equally remarkably, after the plant had been tooled up, this output growth occurred without increases in the capital stock, so at its peak the plant produced over four times as many airframes as its rated capacity! The principal argument of the paper is that labor productivity growth resulted from what Mishina calls "learning by stretching," which is learning that occurs when the firm has to scale up production in a given plant. This argument can be read in two steps. First, intrafirm learning, and not other factors, accounted for productivity growth, and second, this learning can best be interpreted as learning by stretching. I will comment on each of these steps and then on the generality of the case.

Boeing's productivity growth is especially intriguing because many of the factors used to explain productivity gains did not apply. Growing labor productivity could not be explained by changes in the quantity or quality of inputs. The plant and its equipment were complete early in the period analyzed and changed little afterward. Workforce skill declined as skilled craftsmen were replaced by workers new to airframe production, by 1944 overwhelmingly women. Nor can growing labor productivity be cast into doubt by product simplification, quality reduction, or the expansion of outsourcing. The product if anything became more complex, and subcontracting increased very little over time. Learning from other firms was unimportant; Boeing was the leader, and others learned from it. Economies of scale cannot explain much of the productivity growth, because plant capacity did not change after May 1942. Having ruled out changing inputs, external knowledge, product deterioration, and scale economies, Mishina concludes that productivity grew through a learning process occurring within the plant.

This is a strong argument, but it makes more sense after the plant had completely introduced mass production than before. As Mishina notes, before mid-1942, the plant was expanding, mass production was inaugurated, and special-purpose equipment was just coming on line. These innovations were associated with embodied technical change and the learning that comes from mastering that technology. It also seems likely that Boeing, untrained in mass production, learned from other firms, which trained workers and managers adept at interchangeable parts manufacturing, sold Boeing machine tools, and perhaps contracted to mass-produce parts. It is true that important elements of the transition to mass production were complete before the first planes were delivered, but there can be no doubt that much of the early productivity growth, which averaged an amazing 14 percent per month through mid-1942, was due to new mass-production equipment and procedures and probably also to economies of scale as rated capacity was approached. For Boeing, like Ford in the beginnings of mass production, superior equipment, learning from other firms, and scale economies all had parts in improving labor productivity. That said, Mishina is likely right that after mid-1942, the still-remarkable 4 percent monthly growth in labor productivity had another explanation.

What is that explanation? Mishina advances narrative and econometric arguments that Boeing "stretched" its capacity and so increased output relative to capital and labor. It multiplied output with a given capital stock (hence increasing the productivity of capital) by reducing the plant's throughput time (the time interval from the first through the last stage of production) by two-thirds. It increased labor productivity by decreasing the time of parts manufacture and more importantly by reducing the time when workers were either waiting for parts or reworking parts not conforming to the required extreme tolerances. Increases in the productivity of capital and labor had similar causes. Growing interchangeability decreased the time of assembly and increased the velocity of throughput (or labor time and production time in Marx's terminology). This growth had its source in both hardware—new machine tools, dies, jigs, and templates—and "software" changes in work standards and procedures and in tool monitoring. A just-in-time production system also reduced idle labor time and throughput time by improving materials flow and inventory control and by coordinating and dividing subassemblies. To implement and monitor these changes required greater managerial coordination, so that increasing efficiencies in the utilization of capital and direct labor came by means of increasing managerial labor, perhaps growing even in relation to output.

This is a fascinating story about which we'd like to know more. Exactly how were these results obtained? Every capitalist would like to increase the productivity of labor and capital simultaneously, but they evidently do not always do so. How did Boeing do it, and do it at such an extraordinary rate? Mishina demonstrates that there was a challenge and a successful response, but not how that success was achieved. In particular, because managers were the key locus of learning, we need to know more about how they were organized, how they learned, and how they used this learning to restructure input coordination, work rules, worker training, and production flows. Furthermore, Mishina's core claim—that it "is the system of production that embodies learning, not the direct workers themselves"—merits further exploration. Many learning theories agree that the learning process is interactive and systemic, such as short-run learning with existing equipment (David 1975; Lazonick and Brush 1985), long-run learning by doing through purchased capital goods (David 1975), learning by using capital equipment (such as Rosenberg [1982] illustrated for commercial aircraft), and learning by selling that transmits product knowledge (Thomson 1989). But such interactive learning can apply just as much to the individual operation as to the relation among operations. We might test the claim that the systemic coordination was more important than improvements in individual operations by inquiring whether machinists making parts increased relative to workers assembling parts. This was likely so, just as it was so in the prolonged period it took firearms and sewing machines to attain interchangeability in the nineteenth century (Hounshell 1984). But then what distinguishes Boeing's systemic learning from that of Singer or Ford?

The econometric analysis counterposes traditional learning approaches, which focus on labor productivity as function of cumulative output or time since invention, to learning by stretching, which focuses on the novelty of overcoming capacity constraints. Econometrically, Mishina favors the last, because while all approaches are statistically significant, learning by stretching overcomes problems of collinearity in the other two. This formulation expects productivity to grow only when output reaches a new maximum, and so—unlike the other two—does not expect productivity growth when output ceases to grow. Mishina's argument is interesting and sensible; learning responding to the challenge of increasing output in a given plant is likely to augment labor productivity. But the argument raises three issues. First, such learning is not universal; there are incentives and opportunities to learn even with constant output and unchanging plant. Second, the argument raises questions of causality. In learning by stretching, managers learn in an effort to increase both output and labor productivity. When successful, learning today results in expanded output and growing labor productivity in current or later periods. The correlation of the two is then the outcome of a third factor, prior learning. If so, why is one the independent and the other the dependent variable? In an important sense, they can be mutually reinforcing. Productivity increases can speed throughput. Output increases might generate new bottlenecks, which in turn lead to learning that increases later output levels or reduces labor costs at existing output levels. This may account for Boeing's continued productivity growth after the maximum capacity had been reached. In this case, learning forms a cumulative process in which productivity growth, output growth, and learning each feeds into the others. Third, when and with what limits does such learning occur? One important factor omitted in the econometrics is management. If managers were the key learners, would expanding numbers of managers be associated with learning and later productivity increases? Moreover, it seems implausible that Boeing could indefinitely increase output within the same plant. Is there then a "long-run" learning by stretching associated with investment to expand the plant or to build others?

The final issue to address is whether this case has general implications. Its 7 percent *monthly* productivity growth rate was far higher than the 2 percent *annual* growth more typical of short-run learning (e.g., David 1975). Was this exceptionally rapid productivity growth rate so unique that the B-17 had no wider lessons? The challenge to increase output with a given plant may be ever-present or at least present when full capacity is approached, and may lead to labor-saving and capital-saving learning. But it rarely has capacity-exceeding and labor-productivity effects as large as those at Boeing.

I conjecture that Boeing's extraordinary productivity growth resulted from the confluence of two trends, each of which also applies to other firms: wartime expansion and radical innovation over the product cycle. The very context in which Boeing's uniqueness appears—the frantic production for a world war—allows us to draw some more general lessons. The rapid, multidimensional growth in B-17 production was mirrored by that in the economy as a whole in the 1938–50 period, when output, labor productivity, and capital productivity annually grew at the then-unprecedented rates of over 5, 3, and 3 percent respectively (Maddison 1991). The peak of this growth was reached in exactly the years of Boeing's B-17 expansion. In some estimates, from 1941 through 1944 aggregate output grew at 15 percent per year, and the 7 percent growth of aggregate labor productivity was exceeded by the expansion of capital productivity (Maddison 1991; Dumenil, Glick, and Levy 1992).

Wartime expansion was constrained not by demand but by supply factors. Producers could sell all they could make. Yet their expansion was constrained by the scarcity of labor, a problem against which Boeing fought constantly. Producers were also constrained by the uncertainty of whether major private capital investments would be warranted after the war, and perhaps additionally by the scarcity of investment funds. For one or both reasons, private investment was modest; the government was key to Boeing's investments. In this demand-abundant, supply-constrained context, firms had incentives to use capacity more fully. In more typical times, excess capacity exists, creating less pressure to produce beyond capacity, especially when this would lead to rising wage costs. At the same time, retained earnings allow investment to occur in anticipation of future demand.

Boeing's experience reflected this wartime productivity boom, but took it to a higher level. In this Boeing shared features with other firms developing new products. Even if demand-constrained growth is normal in capitalist development, firms in the market-expansion phase of product cycles face strong excess demand. Here particularly rapid output growth and labor-productivity growth often occur together, likely accompanied by short-run learning by doing. In periods of rapid product cycle expansion—which distinguished Boeing from most of the wartime economy—labor productivity rises through learning by stretching and doing in the short-run but also through learning by selling that improves products and increases scale, learning by using, and learning by purchasing new capital goods. Productivity growth is especially rapid when the new commodity comes to be produced in a radically different kind of production process, such as in sewing machines in the 1860s and 1870s, automobiles in the 1910s, and airframes in the 1940s.

In my conjecture, Boeing's uniqueness combines the penetration phase of product cycles with the transition to a particular kind of mass production in the context of a supply-constrained, wartime economy. Other war industries expanded output and exceeded capacity, but often without the same labor-productivity increases. Firms introducing assembly-line techniques to produce new commodities dramatically increased labor productivity but not capital productivity. Ford introduced such assembly-line procedures to make B-29s in World War II. Boeing did not; its investments were more flexible, embodied more in management than in hardware. Its output accelerated more quickly as a result. Boeing thus benefited from three circumstances each of which has broader application: wartime, supply-constrained economies; new products facing rapidly growing markets and mass-production requirements; and organizational innovations that reduced fixed capital expenditures and, as Boeing anticipated, eased movement into other new products. These circumstances can occur separately; Boeing grew by combining all three.

References

David, Paul. 1975. *Technical Choice, Innovation, and Economic Growth.* London: Cambridge University Press.

Dumenil, Gerard, Mark Glick, and Dominique Levy. 1992. Stages in the Development of U.S. Capitalism. In *International Perspectives on Profitability and Accumulation,* ed. Fred Moseley and Edward N. Wolff, 42–65. Aldershot, England: Elgar.

Hounshell, David. 1984. *From the American System to Mass Production, 1800–1932.* Baltimore: Johns Hopkins University Press.

Lazonick, William, and Thomas Brush. 1985. The "Horndal Effect" in Early U.S. Manufacturing. *Explorations in Economic History* 22:53–96.

Maddison, Angus. 1991. *Dynamic Forces in Capitalist Development.* Oxford: Oxford University Press.

Rosenberg, Nathan. 1982. Learning by Using. In *Inside the Black Box,* 120–40. Cambridge: Cambridge University Press.

Thomson, Ross. 1989. *The Path to Mechanized Shoe Production in the United States.* Chapel Hill: University of North Carolina Press.