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How Much Did the Liberty Shipbuilders Learn? New Evidence for an Old Case Study

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This paper offers some new estimates of the contribution of learning to the rapid increases in labor productivity observed in the construction of Liberty ships during World War II. The study exploits new data on physical capital investment and vessel quality constructed from contemporary records held at the National Archives. Estimates of the rate of learning are shown to be sensitive to the inclusion of the new capital data, and data on vessel quality provide evidence that part of the measured productivity increases were secured at the expense of quality.

I. Introduction

Numerous empirical studies of productivity growth have shown a tendency for productivity to rise with cumulative output, particularly at early stages of production (see, e.g., Dutton, Thomas, and Butler 1984; Jovanovic and Nyarko 1995). To engineers and managers, this phenomenon is known as the start-up curve, but economists most often refer to it as the learning curve, or learning by doing. Implicit in economists' choice of terminology is the judgment that a causal relationship has been found: producers learn from experience, and cumulative produc-

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tion is a good measure of experience. However, numerous difficulties involved in measuring the sources of productivity growth raise the possibility that much of what has been attributed to learning by doing in empirical studies may instead be measurement error.

Several careful studies of apparent learning curves lend credence to this concern. Lazonick and Brush (1985) examine productivity in a nineteenth-century cotton mill, concluding that David's (1973) earlier attribution of productivity growth to learning was mistaken. Bell and Scott-Kemmis (1990) muster a variety of qualitative evidence to suggest that productivity growth in the wartime airframe and shipbuilding industries was due to numerous factors other than on-the-job learning. Mishina (1999) provides quantitative evidence that capital investments mattered for wartime productivity growth at Boeing's Plant No. 2. Most recently, Sinclair, Klepper, and Cohen (2000) find that variations in productivity growth rates across more than 1,000 products of the specialty chemicals division of a modern Fortune 500 company are largely attributable to variations in process research and development rather than to variations in rates of learning by doing.

This paper brings new evidence to bear on a classic case study in learning: the Liberty shipbuilding program of World War II. The main contributions of this paper rest on a new, disaggregated data set constructed from contemporary worksheets, reports, and correspondence contained in the records of the U.S. Maritime Commission (USMC) and the records of the U.S. Coast Guard currently housed at the National Archives. Extensive data collected at the level of the individual ship include a quantitative measure of vessel quality, and shipyard data include new information on investment in physical capital.

The empirical analysis focuses on two omissions in previous research: investment in physical capital and variations in product quality. First, I show that capital deepening was much more extensive than has been assumed. Ship construction was well under way before the shipyards themselves had been completed, and additional capital investments accounting for almost two-thirds of the terminal capital stock were undertaken well into the ship construction program. Second, part of the measured increase in productivity was secured at the expense of quality. Incentive payments for fast work led to poor supervision and defective welding. As a result, over 13 percent of the Liberty fleet developed fractures, which in some instances caused the affected ship to sink. I link productivity to the probability that a Liberty ship developed fractures, suggesting that a trade-off of quantity for quality was made.

The contribution of capital investment to measured productivity growth was much larger than the contribution of quality changes to productivity mismeasurement. The former accounts for as much as half of the measured increase in labor productivity, and the latter induces mismeasurement equivalent to only about 5 percent of observed productivity growth. As a corollary to the larger role attributed to capital, the inclusion of the capital investment data diminishes the importance of learning. Without capital data, a ceteris paribus doubling of cumulative output is estimated to increase monthly output by 41 percent; the inclusion of capital reduces this estimate to about 22 percent. These findings are subject to two caveats. First, comovements in capital and standard measures of experience make it quite difficult to separate their effects reliably. Second, my empirical analysis continues to omit other sources of productivity growth—among them, training, R & D, and new technology—that may have also played an important role. If, as Rosenberg (1976) has suggested, coefficients on conventional measures of experience are biased because they are correlated with omitted variables, the inclusion of capital investment has reduced, but not eliminated, that bias.

II. The Liberty Ship Miracle

In 1941, the USMC embarked on a massive expansion of the merchant marine fleet under the auspices of the Emergency Shipbuilding Program. The standard Liberty ship, an all-welded cargo ship with a displacement of 7,000 tons, was the centerpiece of this program. Over a four-year period, 16 U.S. shipyards delivered a total of 2,699 ships, by far the largest production run of a single ship class. Of these, 119 vessels—tankers, colliers, and aircraft and tank transporters—had modifications to the standard Liberty ship design. In addition, a small number of the standard Liberty cargo ships were converted to hospital ships, troop carriers, or training ships. In some cases, the Emergency shipyards carried out these conversions; in others, the ships were delivered to the navy incomplete.

A revolutionary aspect of the Liberty shipbuilding program was that a substantial portion of ship construction was undertaken off the ways (the berths in which the keel is laid and from which the ship is eventually launched). Most yards had a linear "conveyor belt" plan. Steel plates and shapes entered a holding area in the yard on its inland side and passed through a large prefabrication area, where major sections of the ship were constructed. The sections were then transported on rails or by movable cranes to one of the ways, where large cranes lifted them onto the hull for final assembly. Welding constituted the bulk of this work. A Liberty ship contained almost 600,000 feet of welded joints, and welding labor accounted for about one-third of the direct labor employed in construction (Statistics and Reports Unit 1944).[1] Once the main structures were completed, the vessel was launched and moved to the outfitting docks nearby. Another keel was typically laid on the vacant way within 24 hours. At the outfitting dock, final painting, joinery, and electrical work were completed, and rigging and lifeboats were added. The same day on which final outfitting was completed, the ship was delivered to a representative of the USMC, boarded by its crew, and sent to join one of hundreds of convoys crossing the Atlantic or the Pacific.

Output at the shipyards was primarily constrained by the number of ways at the yard and the length of time a ship spent on the ways before it was launched. Prefabrication of major components of the ships reduced considerably the time ships spent on the ways, greatly increasing the productive capacity of the yards. One ship was launched only four days and 15 hours after its keel was laid.[2] Labor productivity was also remarkably high by prewar standards since the new prefabrication techniques allowed many tasks to be carried out more conveniently in inland work areas. For example, metal plates could be held in positions that allowed for automatic welding or made manual welding easier.

Economists have been interested in the Liberty ship program primarily because of the dramatic increases in labor productivity that were observed over a very short period of time. The phenomenal increase in labor productivity experienced during the Emergency Shipbuilding Program, first brought to the profession's attention by Searle (1945), is now well known. Over the course of three years, labor productivity on Liberty ships rose at an average annual rate of 40 percent. Production time fell even more rapidly. While the first ships produced in each yard required more than sixth months from keel laying to delivery, only 30 days were required by late 1943 (see figs. 1 and 2). For over 50 years, economists have attributed these dramatic gains to learning by doing.

Rapping (1965) is most closely associated with the learning-by-doing interpretation of productivity growth in the Liberty ship program. Rapping proposed a yard-specific production function of the form

[1] Bunker (1972) describes the production process at the Kaiser Permanente Yard in Richmond, Calif. At that yard, 61 percent of the ship was prefabricated, with more than 152,000 feet of welding conducted in preassembly areas. A total of 97 prefabricated sections, each weighing up to 250 tons with "all interior fittings—even mirrors, bunk ladders, portholes, washbasins and radiators—already installed" (p. 13), were transported between the preassembly areas and the ways.

[2] This was the *Robert E. Peary*, built in November 1942 at Kaiser Permanente's number 2 yard in Richmond, Calif. At the time, Permanente's average construction time was almost 50 days. The construction of the *Robert E. Peary* was a propaganda effort designed to show that the USMC could always produce ships faster than they could be destroyed. In fact it could not, because there was neither enough steel nor sufficient capacity to manufacture engines at this pace. See Bunker (1972) for an account of the special circumstances under which the *Robert E. Peary* was built.

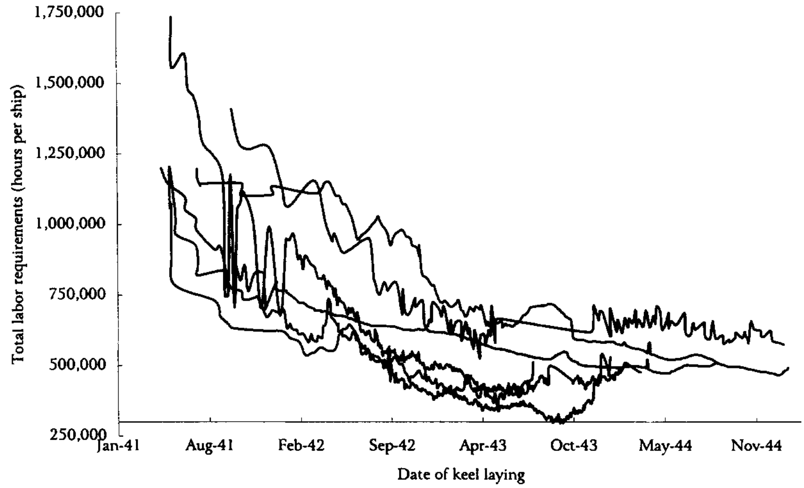

FIG. 1.—Standard Liberty ships labor productivity, six yards. The six yards are those for which capital data are available and that form the focus of study in this paper. See Searle (1945), Lane (1951), or Lucas (1993) for graphs of other yards. All ships delivered incomplete or modified are excluded.

$$y_{it} = Ae^{\lambda t}W_{it}^{\alpha}L_{it}^{\beta}Y_{it}^{\gamma}, \tag{1}$$

where y_{it} is annual deliveries of yard i, W_{it} is the number of ways in operation at time t (his proxy for the stock of capital), L_{it} is the annual rate of physical labor input in hours, and $Y_{it} = Y_{it-1} + y_{it-1}$ is cumulative yard output. Rapping estimated the parameters of the production function using pooled annual data for 15 yards, obtained from Fischer (1949). His analysis was in line with earlier findings by Searle. Each doubling of cumulative output was associated with an increase in annual deliveries of between 7 percent and 27 percent (the point estimates of γ ranged from 0.11 to 0.34), depending on specification, with a mean of 17 percent. Moreover, this apparent learning effect was robust to the inclusion of calendar time, which had no significant impact on productivity. Argote, Beckman, and Epple (1990), using monthly data also constructed from Fischer's statistical summary, reached even stronger conclusions about the importance of learning. Estimating the same specification as (1), they obtained a value for γ of 0.44. Thus each doubling of cumulative output was associated with a 36 percent increase in monthly deliveries.

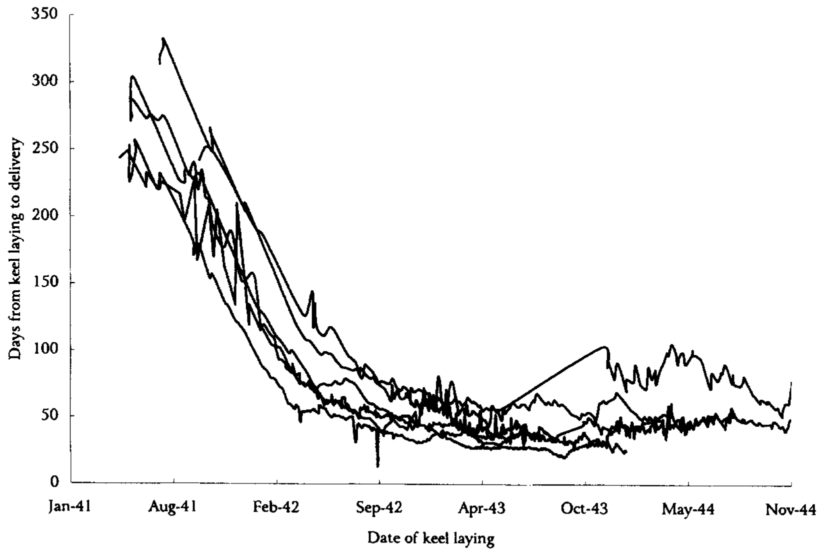

FIG. 2. —Standard Liberty ships production speed, six yards (see note to fig. 1)

III. The Missing Data: Capital Investment

The absence of data on capital has encouraged the perception that none of the increases in productivity at the yard level can be attributed to the familiar mechanism of capital deepening. Rapping (1965) and Argote et al. (1990) used the number of authorized ways in each yard as a proxy for the capital stock, a measure that exhibits almost no variation over time for individual yards. I now have substantial evidence that the number of ways is in fact a crude proxy for capital. Table 1 provides three measures of infrastructure per way for seven large yards. Crane capacity—the major constraint on the size of prefabricated components—varied from 22 tons to 46 tons per way; expenditures on machinery and equipment varied from $286,000 to $811,000 per way; and the size of prefabrication areas varied from 17,200 square feet to 66,400 square feet per way. It is evident that the four yards with above-average productivity had significantly more infrastructure than the three least productive yards.

A. *Authorizations for Increased Capital*

Of course, differences across yards do not show that capital can account for increases in productivity over time. If capital were constant over

TABLE 1
FACILITIES PER WAY FOR SEVEN YARDS

	Crane Capacity (Tons per Way)	Equipment (Thousands of Dollars per Way)	Prefabrication Plant (Thousands of Square Feet per Way)
	A. Four Yards with Above-Average Productivity in the 12th Round		
Calship	34.3	679	27.7
North Carolina	44.7	765	30.2
Oregon	46.5	689	66.4
Permanente	40.0	593	53.7
Four-yard average	41.4	682	44.5
	B. Three Yards with Below-Average Productivity in the 12th Round		
Bethlehem-Fairfield	34.0	811	33.4
New England	22.4	579	17.2
Todd-Houston	24.7	286	32.7
Three-yard average	27.0	558	27.7

SOURCE.— Fischer (1948, table 1).
NOTE.—Productivity comparisons are made for the twelfth round of the ways. Planners at the USMC typically thought in terms of "rounds of the ways." The first ship produced on a particular way belongs to the first round, the second ship to the second round, and so on. It has long been standard practice to compare productivity across yards by averaging over all ships built in a yard at a particular round of the ways, even though the dates on which each yard reached that round varied.

time, yard dummies would control for differences in capital. However, not all investment was carried out at the time the yards were constructed. The U.S. Maritime Commission (1945) notes, for example, that no new shipyards were established during the fiscal year July 1943–June 1944, but $31,142,777 was expended during that period for additional facilities in existing yards. Importantly, none of these funds was used to construct additional ways.

Figure 3 plots Maritime Commission authorizations for capital investment at the six yards for which adequate data are available. New capital authorizations at Calship (panel *b*) followed a typical pattern. On January 10, 1941, the commission approved expenditures of $4.8 million to build six ways and supporting production facilities, adding another eight ways and supporting facilities on April 10 for an additional cost of $4.3 million. However, these expenditures account for only one-third of total investment during the program. On January 16, 1942, investments of $2.8 million were approved for additions to the prefabrication plant and expanded electrical and automatic welding facilities. These expenditures were approved after 19 keels had been laid and five ships had been launched. On June 16, 1942, another $1.9 million was approved to install new cranes that would enable the yard to preassemble larger components and to install additional welding equipment on ways and preassembly platforms. Fifty keels had already been laid prior to this investment. Additional authorizations, between May 1941 and Jan-

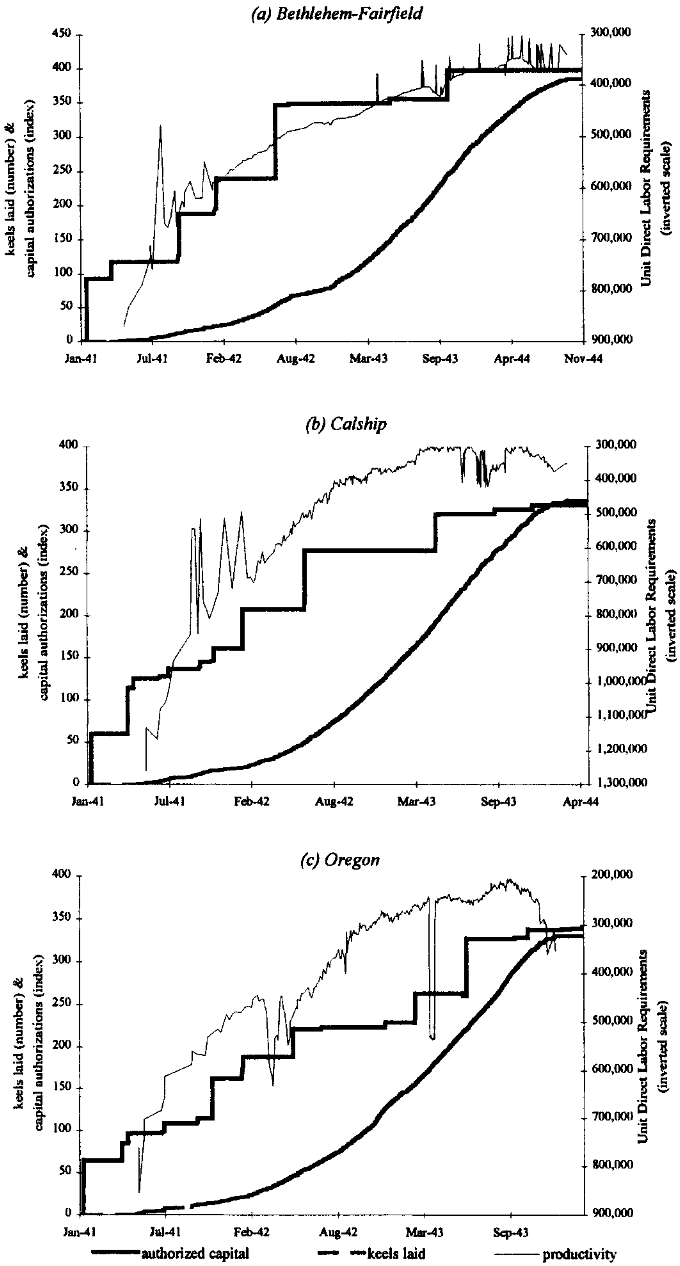

FIG. 3.—Capital, experience, and unit labor requirements, six yards

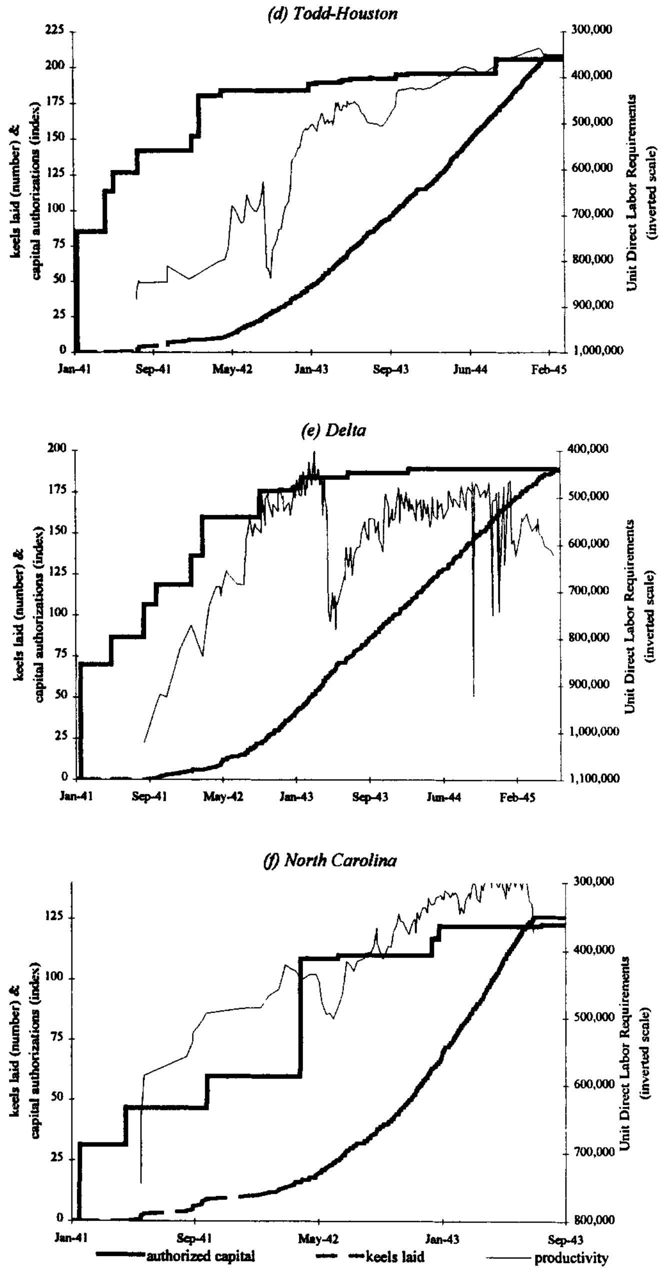

FIG. 3.—*Continued*

uary 1943, accounted for a further $8.2 million expansion of capital. Finally, $4.7 million of new capital was authorized in April 1943. Intended to facilitate conversion of the yard to production of the more complex Victory cargo ships, the additional capital was also available for Liberty ship production.

The reader should note that figure 3 can mislead in several ways. First, all appearances to the contrary, the panels do not show a stronger relationship between capital authorizations and labor productivity than between cumulative output and labor productivity. In fact, capital and experience are each equally capable of providing good within-sample predictors of productivity. Second, delays between authorization of investment and the installation of new capital imply that figure 3 overestimates the speed with which capital was expanded. Third, the graphs show frequent large but short-lived shocks to labor productivity. The new ship-level information allows most of these shocks to be explained by design modifications (most large negative shocks) and ships delivered incomplete for subsequent conversion by the navy (most large positive shocks). One interesting exception is the large negative shock to productivity experienced by Oregon in April 1943. This shock represents eight vessels on which construction was started by another yard in Vancouver; the ships were towed to Portland and completed there.

B. *Time-to-Build Delays*

Time-to-build delays were substantial and clearly had a significant impact on labor productivity. In each yard, construction on the first round of Liberty ships began while the yard itself was still being built. Because prefabrication buildings and cranes were often not installed when a yard began ship construction, a large proportion of the production of first- and second-round ships took place on the ways. The result was that the earliest ships in each yard spent longer on the ways, they were produced using more labor-intensive techniques than ships produced after the yard was completed, and labor productivity was lower.

There are no direct data on how long it took to complete construction of a new yard, nor on how many ships were affected, but both were clearly substantial. In August 1942, for example, Vice Admiral Howard L. Vickery, vice-chairman of the USMC, testified to the Truman committee that "it had been our experience from the yards we had put in that it takes about a year to put a yard in and get really producing" (U.S. Senate 1942, p. 251). If this was generally true, productivity on as many as the first 10 ships produced in each yard may have been adversely affected by time-to-build delays.

Similarly, there are no direct data on the extent to which productivity was affected. However, construction progress reports for South Portland

Shipbuilding Corporation provide some illustration. The yard laid its first Liberty ship keel on September 24, 1941; yet on January 7, 1942, only five of seven cranes in the construction plans had been delivered, and only three of them were operational. Four ships were being constructed at the time, on ways 1–4, but the keels on ways 2 and 3 were being constructed largely from manual welding. While the effect on labor productivity is not known,[3] we do know that the ships produced on ways 1 and 4 were launched 233 and 221 days after keel laying, and the ships on ways 2 and 3 took 256 and 272 days.[4] Evidently, production techniques were different for the first round of the ways, and it would be wrong to attribute to learning by doing all the productivity increases observed as yards progressed from the first to the second round. In fact, Lane (1951, p. 232) simply notes that the first round of ships "was often built while the yard was still under construction" and disregards them in making his comparisons of productivity.

C. *Investment Decisions: Did Experience Play a Role?*

Capital deepening over the life of the Liberty ship program was extensive and is clearly correlated with cumulative output. Thus point estimates of the coefficient on cumulative output obtained from ordinary least squares regressions of a log-linearized version of equation (1) might be expected to correspond fairly precisely to the elasticity of output with respect to capital. Yet one might object that some or even all of the incremental investment could have been the direct result of production experience enabling managers to identify capital constraints. That is, the effects of learning by doing might just be embodied in capital. Indeed, Vice Admiral Vickery testified to the Truman committee that additional capital expenditures were often a result of "everybody thinking of something new they wanted ... like the youngster with candy who wants more" (U.S. Senate 1943, p. 912). Lane (1951, p. 473), noting possible interyard spillovers of investment decisions, also pointed out that additional capital expenditures were often suggested by Vickery himself as he "went from yard to yard, telling each of them what was being done better elsewhere."

However, closer analysis of the data clearly shows that all major in-

[3] The establishment of South Portland was so disorganized that its management was soon replaced, at which time the yard changed its name to the New England Shipbuilding Corp. Probably because of the disorganization, audited productivity data were not collected for the first eight ships.

[4] The information is contained in attachments to Allen (1942), who commented in a letter to Vickery that "we are preassembling our material in sections as much as is possible. However, due to the fact that much of our preassembly area is either unserviced by cranes or is unavailable due to incompleted facilities, we are limited to a great extent in performing this work" (par. *d*).

cremental investments were direct and immediate responses to increases in the scope of the Emergency Program mandated by Congress. Lane (1951, pp. 40–71) documents the series of expansions in the scheduled production of Liberty ships that took place in 1941 and 1942. Calship's experience is representative. On January 3, 1941, the U.S. government announced plans to supply 200 ships to the British under a lend-lease arrangement. Calship won its first contract for 31 ships several weeks later. On March 27, 1941, Congress approved the Defense Aid Supplemental Appropriation Act, which provided funds to construct an additional 200 ships for the British. A new contract with Calship, dated April 17, 1941, called for an additional 24 ships. The Japanese attack on Pearl Harbor on December 7, 1941, immediately generated another wave of expansion as the United States entered the war. On January 16, 1942, Calship won a new contract for an additional 109 ships. Finally, unexpectedly heavy losses to torpedo attacks in the Atlantic during the spring of 1942 generated a new round of contracts in June of that year, with Calship contracting for 60 more ships on June 16, 1942. These new contracts for ships uniformly coincide with authorizations for the major capital expansions of April 10, 1941, January 16, 1942, and June 16, 1942. Moreover, there is documentary evidence that the former motivated the latter. For example, J. E. Schmeltzer, a senior member of the USMC Technical Division, observed that the January 1942 incremental investment in Calship was necessary "to accelerate the ship construction schedule ... to cover the increased scope of the plant and facilities for the purpose of facilitating the assembly of hulls; all in relation to the augmented and accelerated shipbuilding program." In June 1942, C. W. Flesher, West Coast regional director for construction, commented that the June 1942 expansions at Calship were necessary "in order to increase the deliveries of ships to the largest number possible within the physical limitations of [Calship]."[5]

IV. Sources of Growth: Capital versus Experience

This section reports attempts to allocate productivity growth between the two main sources of learning by doing and capital investment. I take the familiar approach of estimating a temporal production function, which I assume takes the form

[5] Both quotes are taken from untitled typescripts containing summaries of USMC minutes (Schmeltzer's dated January 18, 1942, and Flesher's dated June 11, 1942) located in the records of the Historian's Office, box 32, National Archives, records of the U.S. Maritime Commission, RG178. Almost identical justifications accompany requests for, and approvals of, additional facilities at Todd-Houston (Vickery 1943*a*), Jones-Brunswick (Vickery 1943*b*), and Oregon (Oregon Shipbuilding Corp. 1942, p. 1).

$$\ln y_{it} = A_i + \alpha \ln K_{it} + \beta \ln L_{it} + \gamma \ln E_{it} + \epsilon_{it}, \quad (2)$$

where y_{it} is monthly deliveries of yard i, K_{it} is the stock of physical capital, L_{it} is the monthly rate of physical labor inputs, and E_{it} is a measure of experience to be discussed below. The important distinction between equations (1) and (2) is that the latter specification incorporates a measure of all physical capital structures and nonstructures whereas the former incorporates only a subset of structures. The specification of (2) allows for yard fixed effects. As in Argote et al. (1990), the disturbance term is assumed to exhibit up to third-order yard-specific serial correlation. The monthly output data are constructed by aggregating individual ship data, as explained in the Appendix.

A. *Measurement Issues*

Labor

For a substantial part of the war, many of the Emergency yards were producing ships other than Libertys. For example, beginning in November 1943, over half of the yards began to build Victory ships, and the available employment data do not distinguish employment on the production of Libertys from employment on the production of Victorys. To avoid this mismeasurement problem, it will be necessary to limit the sample period to months in which yards were not actively engaged in the production of Victorys.

Over the course of the war the distribution of employees over shifts varied significantly. According to tabulations from the Bureau of Labor Statistics, most yards began production in 1941 with two construction shifts per day and a six-day week. During 1942, a 21-shift week gradually became the norm. Then, in December 1943, overcapacity at the yards persuaded the USMC to immediately abolish Sunday employment[6] and to discourage the employment of construction labor on the graveyard shift (in which labor was generally held to be less productive). By July 1944, only a skeleton crew remained at night. These changes in the distribution of labor inputs across shifts obviously induce corresponding changes in capacity utilization that affect the correct measure of the flow of capital services per month

Capital and labor will both be treated as exogenous. A case has already been made for the exogeneity of capital, which was ultimately chosen by the USMC. But the yards themselves were allowed to hire and dismiss labor, and in this setting the usual inference is that profit-maximizing

[6] The North Carolina yard was granted a permanent exemption and continued to employ construction workers on Sundays. Other yards were given temporary exemptions on occasions.

firms will hire more workers when productivity shocks are positive and will dismiss workers in the face of negative productivity shocks. The extent to which the joint determination of output and employment causes estimation problems depends, of course, on the sensitivity of labor demand to productivity shocks. The standard solution is to instrument for labor hours with wage rates. However, the yards were regional monopsonists in the labor market, so wage rates are not valid instruments. Fortunately, I think a strong case can be made for the view that labor demand was in fact largely unresponsive to productivity shocks.

Consider first the limited incentives that firms had to adjust labor inputs. In negotiations over a contract for ship delivery, each yard and the USMC settled on an average production speed and an average labor requirement (called the "bogie hours") for all ships to be delivered under the contract. If the yard met these agreed targets, all production costs were paid, plus a fixed base fee for profits. To encourage rapid production, a bonus of $400 was paid for each day's increase in production speed, and the base fee was reduced by $400 for each day taken beyond the agreed production speed. To encourage labor efficiency, the yard was paid 50 cents for each labor hour saved in production and its fees were reduced by 33 cents for each labor hour in excess of the bogie. However, these incentives were muted by bounds placed on the fees that could be earned. At the beginning of the war, no yard was permitted to earn a fee in excess of $120,000 per ship, and no yard could earn less than $60,000. These bounds, which were lowered and narrowed several times during the war, effectively converted many cost plus variable fee contracts into simple cost plus fixed fee contracts under which there are no incentives to lay off employees during periods of low productivity. Figure 4 shows the maximum, minimum, and actual fees paid for 36 contracts awarded by the USMC. While the caps were not always binding, particularly at the earliest stages of production, in two-thirds of the contracts signed (accounting for 68 percent of the 1,987 ships included in the 36 contracts), either the minimum or maximum fees were earned, and the bogie formula provided no incentive for efficiency.

Bogie contracts provided little incentive to lay off workers.[7] There were also substantial incentives to hoard labor. For much of the war, labor movements were controlled by the War Manpower Commission (WMC). If a shipyard worker wanted assistance to relocate, a certificate of availability had to be obtained from the WMC. Since one of the easiest ways to get the certificate was for a worker to show the WMC that he or she was not currently employed full-time, a yard could limit the loss

[7] In a May 1944 letter to President Franklin Roosevelt, Henry J. Kaiser (whose companies ran six USMC yards) pressed the government to substitute competitive bidding for the bogie contracts, a policy that, Kaiser argued, would put an end to labor hoarding. The transcript of the letter is an exhibit in House (1946).

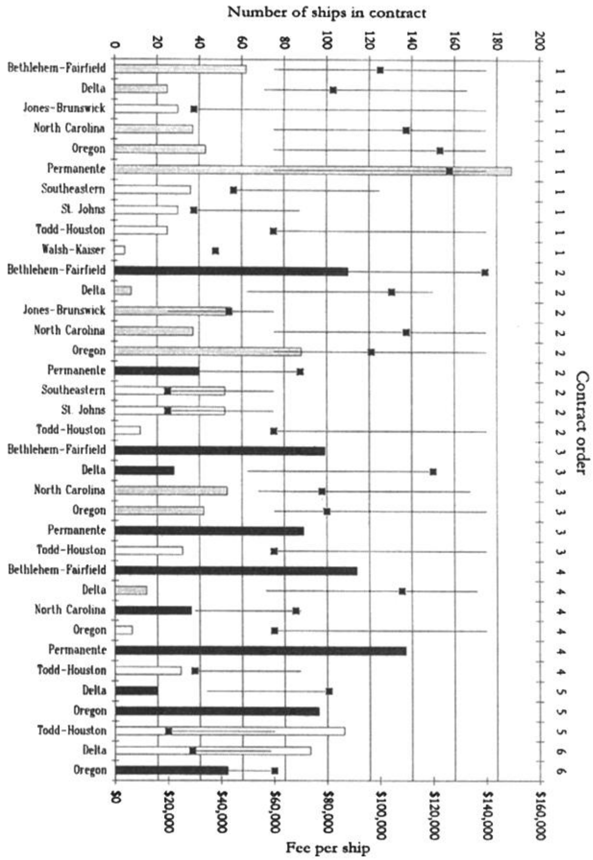

FIG. 4.—Fees per ship on bogie hour contracts, 10 yards. The horizontal bars show the number of ships ordered in each contract, after amendments (top scale). The horizontal lines span the range of allowed fees (bottom scale), and the marker on each line indicates the actual fees paid. The bars are shaded dark when at least 90 percent of the maximum fee was paid, are shaded light when the minimum fee was paid, and have intermediate shading otherwise. The left axis indicates the yard with which the contract was signed. The right axis indicates whether the contract was the first, second, etc., to be signed with the yard. Because certain expenses were invariably disallowed by the USMC, fees paid in excess of 90 percent of the maximum generally could not be raised by increased productivity or production speed. After April 1942, when the Renegotiation Act was passed, yards also knew that any fees earned could be further reduced. Between November 1943 and May 1947, the fees shown in the figure were reduced by an average of 40 percent. "Excess" fees were taxed at a marginal rate of 80 percent. The average tax rate on fees was approximately 65 percent. Source: author's calculations, based on testimony given in House (1946).

of skilled employees who wanted to move simply by keeping them employed full-time. On the other side of the coin, a yard that wanted to hire more workers was often required to obtain approval from the WMC, which classified vacancies by degree of urgency. It was, naturally, rather difficult for a yard that had recently let workers go to claim a high degree of urgency for new recruits. Hiring restrictions presented a real danger to the yards: if a yard could not demonstrate that it had an adequate labor force, winning new contracts became more difficult. Inevitably, labor hoarding was a common phenomenon. Evidence of hoarding can be found during 1942, when steel and engine shortages slowed down production at many yards. In the spring of 1942, Admiral Emory Scott Land, chairman of the USMC, began a public campaign against loafing, which quickly led to an acrimonious exchange, largely through the media, between Land and labor leaders. In an attempt to end the dispute, Roosevelt publicly commented that he believed a shortage of steel plates to be the chief cause of idle labor ("President Calls War Output" 1942, p. 1). Following up his public defense of labor with a personal letter to Land dated May 2, 1942, Roosevelt said that "many of the so-called slow-downs in shipbuilding plants are due not to organized labor but to strict orders or suggestions from the foreman or their management that a slow-down would be advantageous because the non-delivery of shapes and plates will cause a lay-off if there is not a slow-down." Land agreed. On May 20 he responded that "inefficiency is one cause [of the slowdown]; lack of material is another cause; and fear of losing some of their good personnel is a third cause" (National Archives, Admiral Land's correspondence files, RG178).

Experience

The most common measure of experience, cumulative output, is the measure used by Rapping (1965) and by Argote et al. (1990). It will also be the primary measure used in this paper. However, its use in estimation of the production function may induce finite sample bias. The term $\ln(Y_{it})$ can be written as $\ln(Y_{it-1} + y_{it-1})$, and $\ln(y_{it-1})$ is correlated with the disturbance term in the presence of serial correlation. Note, however, that

$$\lim_{Y\to\infty} \frac{d(\ln Y + y)}{d(\ln y)} = 0,$$

so the correlation vanishes asymptotically. Another measure of experience, cumulative labor hours, avoids this potential problem, and estimates using it in place of cumulative output will also be reported. The distinction between the two measures is that cumulative output measures

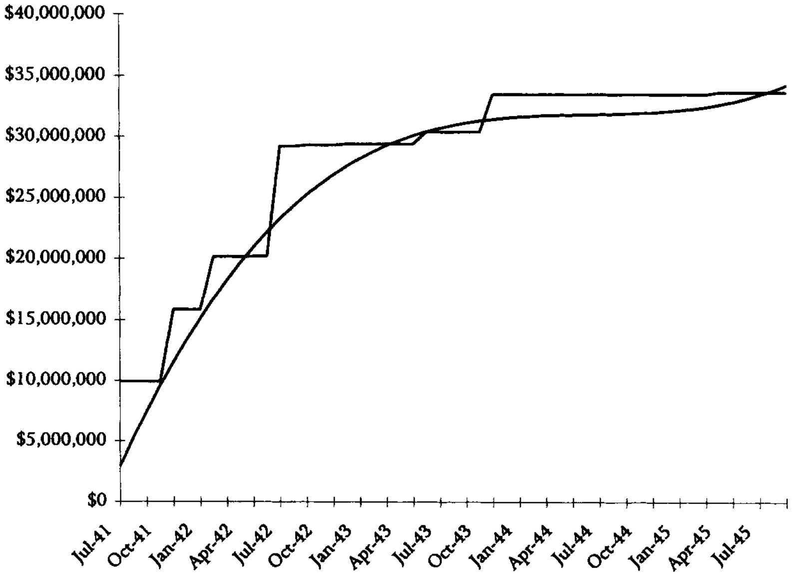

FIG. 5.—Authorized and smoothed capital, Bethlehem-Fairfield

the number of times a task has been done, whereas cumulative employment measures the amount of time spent trying to accomplish the same set of tasks. I do not know of any compelling reason to prefer one measure to the other.

Capital

I do not have capital stock data. The capital authorization data described earlier represent only the *desired* capital stock, in the sense that they document requests for capital, and time-to-build delays were substantial. To capture time-to-build delays, I create a proxy for the installed capital by smoothing the authorization data. This was carried out by fitting polynomial functions of time to the data points on capital authorizations that correspond to the rightmost point of each horizontal segment in the capital data shown in figure 3. Figure 5 plots a typical series for smoothed capital.

A final difficulty, which affects capital in all estimating equations, is that there are no yard-specific price indices, yet the cost of capital undoubtedly varied across yards. Thus, although the discussion of Section III supports the assumption that desired capital is exogenous, it is measured with error. Two approaches present themselves. First, one could

TABLE 2

SURE Production Function Estimates (Experience Proxy: Cumulative Output)

	Rapping	Argote et al.	Dependent Variable: Log Monthly Output in Ship Equivalents			
	(1)	(2)	(3)	(4)	(5)	(6)
Log experience (cumulative output)	.110 (.013)	.44 (.03)	.493 (.025)	.481 (.027)	.291 (.045)	.263 (.037)
Log authorized ways	.293 (.096)	1.15 (.05)	...	...	...	...
Log operating ways	...	...	...	.274 (.236)	...	...
Log capital, K_{it}	...	...	...	...	.743 (.180)	.780 (.154)
Capacity utilization weight, $w_{it} = (6 + S_{it})/7$	...	...	...	...	...	.780 (.154)
Log labor hours	1.11 (.032)	.18 (.04)	.414 (.061)	.422 (.061)	.414 (.057)	.253 (.088)
Wald tests (p-values):						
Col. 3	...	...	...	.656	.000	.000
Col. 4	...	...	...	...	.000	.000
Adjusted R^2	.967	.990	.925	.922	.919	.711
Observations	48	337	182	182	182	149

Note.—Standard errors are in parentheses. Col. 1 reports coefficients from regression 6 in Rapping (1965, table 1). Rapping's regression 6 produced his lowest point estimate for the coefficient on experience, but the specification is closest to that used in the remaining columns of the table. Col. 2 reports coefficients from col. 2 of Argote et al. (1990, table 1). Regressions in cols. 3–6 include yard fixed effects and yard-specific AR(3) errors. Wald tests are tests that the coefficient on experience is the same as the point estimate in cols. 3 and 4. In col. 6 the coefficients on capital and the capacity utilization weights are restricted to be equal. Because total sample R^2 measures can mislead in pooled data, the adjusted R^2's in cols. 3–6 are the *lowest* of six yard-specific coefficients of determination. Total-sample coefficients of determination were all in excess of 0.92.

attempt to instrument for capital. However, problems of selecting useful instruments lead to the second approach of ignoring the measurement error. This will, of course, attenuate the role of capital. However, there are reasons to suppose that biases induced by potential measurement error will be small. For example, at least part of the measurement error will be due to systematic proportional differences across yards in the cost of installed capital (due, e.g., to persistent regional differences in nominal wages). The log-linear functional forms employed conveniently separate out these differences and allow them to be captured by yard fixed effects.

B. *Estimation*

Columns 3–6 of table 2 report estimates of equation (2) using cumulative output as a proxy for experience. Seemingly unrelated regression estimation (SURE) is conducted to allow for contemporaneous correlation in the disturbances across yards. For comparison, the results for similar specifications estimated by Rapping (1965) and by Argote et al. (1990) are also reported. In my reduced sample of six yards, there is no variation over time in the number of authorized ways, which are consequently confounded with the yard fixed effects. Column 3, which omits any proxy for capital, therefore reports my attempt to replicate the earlier results. As noted earlier, the two previous studies produced rather different estimates of the importance of cumulative output. In particular, Rapping produced consistently smaller coefficients on experience than Argote et al. One can readily show that this difference occurs at least in part because Rapping used annual data whereas Argote et al. used monthly data.[8] My estimate of the coefficient on experience in column 3 is very close to the Argote et al. estimate.

Column 4 uses a proxy for capital constructed from the number of ways in use rather than the number of ways that had been authorized. This proxy is, I think, what previous researchers intended to measure with their way data. However, even though the number of ways in use does rise over time, its inclusion in the regression proxy has no effect on the estimated importance of experience. Note also that Argote et al. obtained a very large value for the coefficient on ways and a very small coefficient on labor inputs, neither of which I can replicate. The reason for this seems to be that their monthly output series was constructed by taking Fischer's (1949) data on average production speed per way and multiplying these data by the number of authorized ways. The use of the same data on the left- and right-hand sides of (2) has obvious implications for the coefficient on ways.

Column 5 introduces the capital series obtained from smoothing the capital authorization data. The main result of interest is that the coefficient on experience declines, from almost 0.50 in the previous columns to 0.29. Wald tests confirm that this decline is statistically significant. Finally, column 6 attempts to account partially for variations in capacity utilization by exploiting data on shift employment. Each month's capital

[8] Recall that cumulative output can be written as $\ln(Y_{it-1} + y_{it-1})$, so that this variable is a nonlinear function of the lagged dependent variable. Temporal aggregation has serious consequences for parameter estimates in this context. The point can best be made by considering the deterministic linear model $y_t = \rho y_{t-1} + \beta x_t$, where the subscript indexes monthly observations. Imagine that data are available only bimonthly, so that the econometrician is forced to regress $y_{t+1} + y_t$ on $y_{t-1} + y_{t-2}$ and $x_{t+1} + x_t$. Some straightforward manipulations yield

$$y_{t+1} + y_t = \rho^2(y_{t-1} + y_{t-2}) + \beta(x_{t+1} + x_t) + \rho\beta(x_{t-1} + x_{t-2}).$$

The coefficient on the lagged dependent variable is biased downward for $\rho < 1$, as it must be in the present application. Note that when $\rho = 0$, no bias is induced by temporal aggregation.

data are given a weight of $w_{it} = (6 + S_{it})/7$, where S_{it} is Sunday employment as a fraction of weekday employment. Because of the log-linear specification, the weights and the capital data are additively separable. One can therefore estimate by restricted least squares and test the linear restriction that the coefficients on unweighted capital and the weights are equal. Column 6 reports the restricted estimate.[9] While the coefficient on labor is now substantially smaller, the main result is much the same as in column 5: the introduction of capital reduces the coefficient on experience, and Wald tests again confirm that the decline is significant.

Introducing the capital data to the regressions uniformly induces a significant reduction in the estimated impact of experience on productivity. Compare, for example, my attempt to replicate previous findings in column 3 of table 2 with the estimates in column 5. The estimates in column 3 indicate that a ceteris paribus doubling of experience would raise monthly output by 41 percent, whereas the estimates in column 5 reduce that figure to 22 percent. At the same time, a doubling of the amount of capital in the yard is estimated in column 5 to raise monthly output by 67 percent. These numbers are somewhat sensitive to model specification. The importance of capital *rises* when adjustment is made for capacity utilization, so that a doubling of capital is estimated in column 6 to induce a 72 percent increase in monthly output; the importance of experience is correspondingly lower, and a doubling of cumulative output is associated in column 6 with a 20 percent increase in monthly output.

Finally, table 3 reports results of the same analysis conducted using cumulative labor hours as the proxy for experience. Although the point estimates on capital appear less plausible than when cumulative output was the proxy for experience, the results are generally consistent: the addition of capital to the regression reduces the point estimate on experience by more than a third, and Wald tests again show that the decline is significant.

V. Were All Liberty Ships Created Equal?

Unobserved variations in quality inevitably introduce measurement error into growth accounting exercises. Random variations in quality that are not affected by production decisions do not need to be measured. In contrast, productivity increases secured at the expense of quality need to be discounted from measured growth rates. Adjusting for the system-

[9] Some observations are lost because of missing data. The restriction is not rejected by a Wald test (p-value .504). The unrestricted coefficient estimates (standard errors in parentheses) are 0.84 (0.18) on unweighted capital and 0.54 (0.39) on the capacity utilization weights.

TABLE 3
SURE PRODUCTION FUNCTION ESTIMATES (Experience Proxy: Cumulative Employment)

	DEPENDENT VARIABLE: LOG MONTHLY OUTPUT IN SHIP EQUIVALENTS			
	(3)	(4)	(5)	(6)
Log experience (cumulative labor hours)	.359 (.040)	.355 (.038)	.228 (.038)	.208 (.050)
Log operating ways	...	−.278 (.299)	...	...
Log capital, K_{it}	...	...	1.040 (.127)	1.117 (.165)
Capacity utilization weight, $w_{it} = (6 + S_{it})/7$	...	...	...	1.117 (.165)
Log labor hours	.542 (.074)	.566 (.072)	.462 (.065)	.343 (.086)
Wald tests (*p*-values):				
Col. 3		.902	.001	.003
Col. 4	...	...	.001	.004
Lowest adjusted R^2	.905	.901	.98	.716
Observations	177	177	177	149

NOTE.—See note to table 2.

atic component of quality change is usually a challenging task. First, one must be able to measure quality. Second, one must be able to show that at least part of any quality variations can be predicted by productivity levels. Finally, one needs to be able to value the predictable changes in quality. In this section, I use new data on the eventual fate of each Liberty ship to show that part of the measured productivity growth was secured by allowing quality to decline. It will turn out that the indicated quality adjustments to measured output per worker are modest in relation to the high measured rates of productivity growth rates. However, because it has long been argued that homogeneity of output is one of the most attractive features of the Liberty ship experiment, this section should be of independent interest.

A. *Fractures in Liberty Ships*

Just as the peak productivity levels were being recorded in the winter of 1942–43, some remarkable hull failures occurred. On January 16, 1943, a tanker, *Schenectady,* split in two while moored in calm water at the outfitting dock at Swan Island, Oregon. A U.S. Coast Guard (1944) report described the incident:

> Without warning and with a report which was heard for at least a mile, the deck and sides of the vessel fractured just aft of the bridge superstructure. The fracture extended almost instantaneously to the turn of the bilge port and starboard. The deck side shell, longitudinal bulkhead, and bottom girders fractured. Only the bottom plating held. The vessel jack-knifed and the center portion rose so that no water entered. The bow and stern settled into the silt of the river bottom.

The ship was 24 hours old.

The *Schenectady* was not the first merchant ship to fracture, although it was certainly one of the more dramatic cases. In fact 10 USMC ships, eight of them standard Libertys, had already suffered a serious fracture by the time of the *Schenectady* incident. But the *Schenectady* fracture was the first to happen in full view of the population of a major city and, hence, the first to attract widespread attention. Portland newspapers of January 17, 1943, reported the story, and publicity about several more serious casualties in the months following could not be suppressed.[10] On February 2, 1943, an editorial in the *New York Journal of Commerce* observed that

> for the last year the Maritime Commission has used the construction records of the Kaiser yards as a sort of whip with which to goad other of the nation's yards into speedier construction. No one will deny that speed is needed in the construction and delivery of ships. However, no matter how speedily a ship is delivered its worth is practically nil if its plates crack, or if for any other reason that vessel must spend thirty to sixty days in a repair yard after one or two trips. [P. 18]

Lane (1951, p. 545) reports that there were "other less sensational fractures during the opening months of 1943." In fact there were many more, and they were to continue throughout the war. By February 1946, 362 ships, over 13 percent of the Liberty fleet, had suffered at least one

[10] Several of these casualties also occurred in calm water. On February 12, 1943, *Belle Isle*, an ore ship, was traveling partly loaded in calm seas. It split across the deck and part way down the sides. A complete rupture was prevented only by rivets on the side seams. Four days later, the new Liberty ship *Henry Wynkoop* fractured its deck while being loaded in New York, and on March 29 the tanker *Esso Manhattan* broke in two just after leaving the entrance to New York Harbor.

major fracture. Of these, 103 ships suffered class I fractures that threatened the structural integrity of the ship.[11]

Following the *Schenectady* incident, the USMC established a Board of Investigation to study the causes of, and provide solutions to, the problem of fracturing. The board immediately funded over 30 distinct research projects at laboratories and universities throughout the country. Interim reports of the Board of Investigation (1944, 1945) have extensive discussions of "locked in stresses" in certain areas of the ship, exacerbated by shifting loads in rough weather and sudden drops in air or water temperature. These stresses were believed to be "relieved" by the crackings. But, as Lane (1951, p. 572) notes, such phrases were "figures of speech used to describe the unknown, just as psychiatrists describe the mysteries of human personality by talking about the need of relieving inhibitions." Despite the uncertainty about the causes of the fractures, the major research effort funded by the board generated numerous important design changes between February and May 1943. These changes, along with additional modifications mandated in January and February 1944, are described in some detail by Lane (1951, pp. 548–50). The effect of the design changes was a decline in the fracture rate from 30 percent for ships with keels laid in February 1943 to about 5 percent only four months later. Figure 6 shows this dramatic decline.

Locked-in stresses will not lead to fractures if materials are strong enough and workmanship is good enough to withstand them. Moreover, stresses resulting from design flaws cannot fully explain several features of the data. Fracture rates varied significantly across yards (see table 4). This variation could be accounted for by systematic variations in steel quality in the mills supplying the yards, an issue that received much attention in 1943 and 1944. However, steel quality cannot be all the explanation because yard differences in fracture rates were clearly related to productivity differences. Figure 7 plots the two measures of fracture rates from table 4 against labor requirements for the first ship built in the eighth round of the ways. The correlation between productivity and fracture rates is clearly visible and is statistically significant at conventional levels. Moreover, fracture rates exhibited a marked tendency to rise during the first two years of the program. In fact, figure 6, which pools data across yards, understates the extent to which fracture rates increased over time within some of the larger yards. These features of the data strongly suggest that, even though design and steel quality

[11] Some vessels fractured as many as five times, and there were in fact over 1,000 fracture incidents, often involving multiple fractures, on the 362 ships. "Design and Methods of Construction" (1947) documents a total of 2,504 fractures in 964 separate incidents.

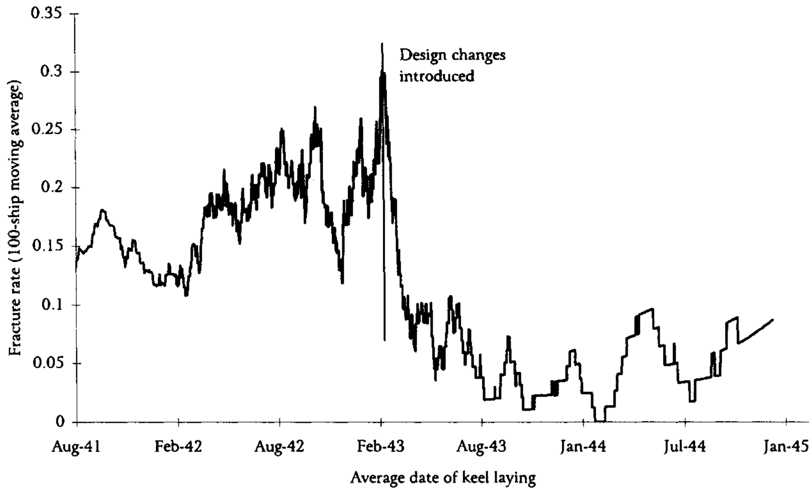

FIG. 6.—Observed fracture rates. The figure was constructed by ordering all ships, irrespective of yard, by date of keel laying. The fracture rate is a moving 100-ship window measuring the fraction of all the ships within the window that eventually produced fractures.

were contributing factors, production practices were related to the fracture problems.[12]

B. *Trading Quantity for Quality*

While experts were talking about locked-in stresses, they were also paying attention to the quality of welding. In fact, the official Coast Guard report on the *Schenectady* incident attributed the fracture to welds in critical seams that "were found to be defective." By the time Tyler (1947) surveyed the fracture problem, the quality of welding had become the central theme;[13] "Design and Method of Construction" (1947, p. 591)

[12] Whether or not a defect in a weld leads to a fracture depends on the size of the defect, the stress, and the toughness of the material. For a given stress, tougher steel can withstand larger defects without fracturing. Modern methods of fracture mechanics can use these parameters to calculate the critical defect size above which a fracture is expected to occur. Most descriptions of Liberty fractures indicate that the cracks were accompanied by loud bangs, which is characteristic of brittle fractures (i.e., failures because of insufficiently tough steel).

[13] Half of Tyler's report is devoted to the topics of welder training, supervision, and welding practices. U.S. Senate (1944, pp. 9943–48) contains fascinating testimony from Robert P. Day, a ship inspector who had worked at several Kaiser yards, about failures to correct welding problems that he reported.

TABLE 4
FRACTURE INCIDENTS BY YARD

		FRACTURE INCIDENTS		SHIPS FRACTURED	
	NUMBER BUILT	Number of Incidents	Incidents per Ship Delivered (%)	Number Fractured	Fractures per Ship Delivered (%)
Bethlehem-Fairfield	384	90	23.4	71	18.5
Jones-Brunswick	85	27	23.7	7	8.2
Calship	336	164	48.8	70	20.8
North Carolina	126	60	47.6	15	11.9
Delta	188	57	30.3	23	12.2
New England	244	72	29.5	10	4.1
Todd-Houston	208	74	35.5	29	13.9
Oregon	330	215	65.2	80	24.2
Jones-Panama	102	14	13.7	6	5.9
Permanente #1 and #2	489	100	20.4	40	8.2
Southeastern	88	23	26.1	8	9.1
St. Johns	82	26	31.7	3	3.7
Total	2,692	922	34.6	362	13.6

SOURCE.—Fracture incidents are taken from "Design and Methods of Construction" (1947, p. 588). Number of ships fractured is taken from Bates (1946) and Board of Investigation (1945).

NOTE.—The table excludes yards producing 20 Liberty ships or fewer.

concluded in the same year that defective workmanship was an identifiable contributing factor in half of the fracture incidents:

> The fractures occurring on the EC2-S-C1 design have been grouped to determine the proportionate contribution of design and workmanship to the number of fractures which occurred. It is impossible to make a breakdown with a clear line of demarcation between the groups because in many cases, poor design details and poor workmanship went hand in hand in their contribution to the fracture. In other cases, awkward design resulted in defective welds because of the difficulty in performing the welding.... It has been possible to make a reasonably reliable judgment regarding the part played by workmanship in 1800 of the 2504 fractures reported occurring on the EC2-S-C1 vessels before August 1945. It was found that in 25% of these cases, no fracture would have resulted had good workmanship been used. In 20% of the cases, there was some question but it was believed that the failure might have been avoided had the workmanship been good.

Defective welds were associated with increased use of automatic welding machines beginning in late 1942. While automatic welding greatly

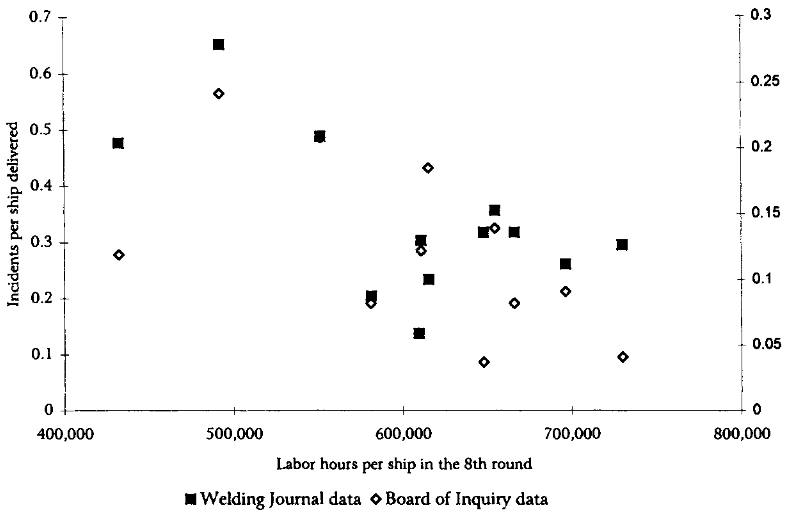

FIG. 7.—Fracture rates and productivity

increased labor productivity,[14] over 50 percent of the fractures are known to have originated in the loading hatches and, as "Design and Methods of Construction" (p. 588) reported, "it was common practice in some shipyards to weld with a Unionmelt machine to within a few inches of the hatch coaming where the automatic equipment had to be stopped. The remainder of the seam was completed by hand welding without further preparation and a saddle weld resulted because of the failure of the welding to penetrate the square-edged butt." Automatic welding in the neighborhood of critical joints was prohibited after February 1943.

However, C. E. Wilson, production vice-chairman of the War Production Board, clearly believed that poor welding was due to more factors than just automation. He visited most of the yards in the weeks following the *Schenectady* incident and documented numerous cases of poor supervision of welders, poor craftsmanship, and even fraud (Tyler 1947; Lane 1951, pp. 544–73). Bonus wage payments for fast work led in some instances to intentionally defective welding and fraudulent actions. In April 1943, Wilson appeared in Baltimore as an expert witness in the civil trial of one of nine welders accused of placing unfused electrodes

[14] "New Welding Technique" (1942) reported that Liberty shipyards were introducing new automatic welding techniques that increased production by over 100 percent. Kaiser Co. (1943) reported that a good welder could turn out about 500 feet in eight hours on a machine weld, compared with 100 feet in the same time by a manual weld.

and slugs of iron in plate grooves and then covering them with superficial welds. The process, known in welding circles as slugging, greatly increases the speed of welding but seriously weakens the joint. The defendant was convicted of "making war material in a defective manner with the intent that his act would hinder, obstruct and interfere with the United States Government in preparing for and carrying on the war" (Wilson; quoted in Tyler [1947, p. 72]) and, being a minor, was sentenced to 18 months in a reformatory school. Wilson found that some welders at the Bethlehem-Fairfield yard in Baltimore had tried to use two electrodes with machines designed for only one. At Calship, poorly skilled welders were found to have been hired on the basis of test plates made by others, and some unskilled welders had skilled friends and relatives take qualifying tests for them.

Not all the blame can be laid on the yard employees. In fact, from the beginning of the program, top administrators in the construction program encouraged greater production speed with the full knowledge that reliability might suffer as a consequence. The American Bureau of Shipping (ABS) was the agency responsible for coordinating safety inspections at the yards. Yet, in early 1942, the ABS issued a statement that explicitly directed its inspectors and the shipyards to favor speed over safety: "It must be recognized, not only by inspectors but also by the building yards, to whom copies of this letter are being furnished, that under the present circumstances early completion of serviceable ships is of greater national importance than the high measure of perfection required for full durability" (quoted in Tyler [1947, p. 17]).[15]

Workers, managers, and even safety inspectors were willing to trade quality for quantity. To assess the magnitude of this trade-off, I have matched data on dates of fractures and losses by enemy action to productivity data for 2,662 Liberty ships. Probit and duration models are estimated to measure the effect of labor productivity and production speed on ship fracture rates.

The probit model is

$$y_{ij}^* = \mathbf{x}_{ij}\beta + u_{ij},$$

$$y_{ij} = \begin{cases} 0 & \text{if } y_{ij}^* < 0 \\ 1 & \text{if } y_{ij}^* \geq 0, \end{cases} \tag{3}$$

where $y_{ij} = 1$ if ship j at yard i developed at least one fracture by February 2, 1946, and $y_{ij} = 0$ otherwise. The regressors include labor hours expended on ship ij or production speed in days; the length of war service,

[15] Tyler (1947, p. 18) notes that the letter was discussed without adverse comment in a meeting of the Production Division of the USMC. John Wilson, assistant chief surveyor of the ABS, testified before the Truman committee (U.S. Senate 1944, pp. 9955–82), where ABS safety procedures came under considerable fire.

which controls for the fact that the observation for each ship is truncated either by the sampling date of February 2, 1946, or by the fact that the ship was lost at an earlier date as a result of enemy action; a dummy variable equal to one if the ship's keel was laid after the design changes of March–May 1943 were instituted; and the date and order of keel laying, to control for possible spurious results arising from the trend in productivity. Yard dummies are included to control for systematic variations in steel quality and for differences in yard practices that were not associated with productivity.

The duration model estimates the hazard rate from a Weibull distribution:

$$\lambda_{ij}(t) = e^{\mathbf{x}_{ij}\beta} v(e^{\mathbf{x}_{ij}} t)^{v-1}, \tag{4}$$

where t is the time that has elapsed since delivery, and v is a parameter to be estimated. The log likelihood function is

$$\ln L = \sum_i \sum_j \{\delta_{ij}[v(\ln s_{ij} + \mathbf{x}_{ij}\beta) + \ln v] - \exp[v(\ln s_{ij} + \mathbf{x}_{ij}\beta)]\}, \tag{5}$$

where $\delta_{ij} = 1$ if the ship developed fractures and $\delta_{ij} = 0$ otherwise; s_{ij} is the time between delivery and whichever came first among fracture date, war loss, and the end of the sampling period. The list of regressors is the same as for the probit model, with the exception of length of war service.

Table 5 reports the estimates of equations (3) and (4). The coefficients on labor hours, production speed, war service, and design changes are all significant and have the expected sign. In particular, a reduction in labor hours or time expended on the production of a ship is strongly associated with an increase in the likelihood that the ship subsequently developed fractures. This link is particularly strong for ships built prior to the design changes of early 1943. For example, when other variables are held at the sample means, a reduction in labor hours per ship from 1.25 million hours to 350,000 is associated with an increase in the fracture rate of from an initial 6 percent to 20 percent. The design changes mandated in the spring of 1943 significantly reduced the predicted risk of fractures. When war service and total labor requirements are held constant at the sample mean, the design changes reduced the probability of fracturing from 18 percent to just 4 percent.

Coefficients on yard dummies (not reported) exhibit large fixed effects, and the hypothesis of no yard effects is strongly rejected. Moreover, the relationship between productivity and fracturing is robust to the inclusion of calendar time and production order. Results are almost identical (in regressions not reported) when data enter in logarithms, when direct labor hours are used instead of total labor hours, when time to launching is used instead of time to delivery, and when the

TABLE 5
DETERMINANTS OF FRACTURE PROBABILITIES AND HAZARD RATES IN LIBERTY SHIPS

	PROBIT*		WEIBULL DURATION MODEL	
	(1)	(2)	(3)	(4)
Constant	−.70	−.78	−2.07	−2.95
	(.37)	(.27)	(.96)	(.62)
Labor hours per ship (millions)	−.63	...	−1.83	...
	(.29)		(.77)	
Production speed (hundreds of days)	...	−1.28	...	−2.43
		(.41)		(.97)
War service (years)	.06	.05	...	...
	(.02)	(.02)		
Design changes	−.62	−.55	−1.48	−1.38
	(.12)	(.12)	(.27)	(.28)
Date of keel laying (years since first keel laid)	−.21	−.27	−.43	.35
	(.15)	(.14)	(.42)	(.36)
Order of keel laying	−.00	−.00	−.00	−.00
	(.00)	(.00)	(.00)	(.00)
v	...	...	.82	.81
			(.06)	(.06)
Observations	2,662	2,654	2,662	2,654
Log likelihood	−819.2	−816.4	−1,174.2	−1,174.4

NOTE.—All regressions include yard dummies. Standard errors are in parentheses. War service is years to delivery to end of sampling period or February 2, 1946, whichever comes first. Design changes equals zero if keel was laid before May 1943, one otherwise. Eight ships delivered by Oregon had been partially built by Kaiser-Vancouver; data on production speed are not available for these ships.

* y equals one if the fracture was reported before February 2, 1946, and zero otherwise.

binary model is estimated by logit. Note also that the parameter v in the duration model is significantly less than one, indicating that hazard rates declined with time in service. Declining hazard rates point to defects, rather than stress in service, as a significant cause of fractures.

C. *Adjusting Productivity Growth Estimates for Quality*

To estimate the extent to which the official statistics overstate productivity growth, the probability of a fracture for each ship is predicted from the duration model in column 3 of table 5. Ships within each yard are standardized by predicting the probability that a fracture will occur within 2.2 years. Productivity data can then be adjusted for quality by combining these predictions with estimated costs of fractures, in labor hour equivalents. The following assumptions are then used to transform fracture probabilities into labor hour equivalents. Data from the Economics and Statistics Division (1946) indicate that the majority of ships were repaired between two and four months after the date of fracture. I therefore assume that one cost of a fracture, irrespective of the class of fracture, is the loss of three months (out of an average of 2.2 years) of ship service time. The labor cost of lost service for a fractured ship is calculated using each yard's mean labor requirement. Adding these imputed costs to the direct labor cost of repairs, one could then adjust measured labor productivity for quality by weighing the labor cost of each type of fracture according to the shares of class I and II fractures in all incidents of fractures reported and multiplying the weighted sum by the yard-specific predicted probability of a fracture appropriate for a vessel with the indicated labor requirement.

The weak link in this chain of adjustment is that I have no data on hours required to effect repairs of fractures. I think it is reasonable to assume that direct repairs did not exceed 150,000 labor hours for a class I repair or 50,000 hours for a class II repair. These are, after all, as much as 50 percent and 17 percent, respectively, of the cost of constructing an entire ship. Even with these upper limits, the effects of quality adjustment on the productivity numbers are modest. For example, a ship produced in 1941 with one million hours of labor has a predicted fracture probability of 7 percent, whereas one produced in March 1943 using 450,000 hours of labor has a fracture probability of 20 percent. The unadjusted productivity increase is 122 percent and the adjusted productivity increase is no less than 113 percent; thus the raw data contain a measurement error equivalent to no more than 6 percent of measured productivity growth. Moreover, the gap between measured and quality-adjusted productivity growth obviously diminished markedly after the design changes of early 1943. However, the implied increase in quality-adjusted productivity after March 1943 should be attributed to the research program authorized by the Board of Investigation.

VI. Conclusions

Growth accounting in the presence of learning by doing is fraught with danger. Omitting factors that may be correlated with time or with cumulative production would cause a researcher to mistakenly attribute their effects to learning. This paper exploits new evidence on the Emergency Shipbuilding Program of World War II to show that this classic case study of learning suffers from omitted variable bias. Conventional wisdom, which attributes virtually all productivity growth in the Liberty ship program to learning, derives from studies that did not incorporate the extensive capital investments that took place during the war. The inclusion of capital in estimates of functions of production and labor requirements reduces the estimated size of the learning effect by about 50 percent. I also show that the quality of Liberty ships, as measured by the fracture rate, declined systematically with labor productivity and production speed. Contrary to conventional wisdom, then, all Liberty ships were not alike. However, the extent of mismeasurement induced by omitting quality changes appears to be small.

My estimates of the size of the learning effect should continue to be treated with caution. First, cumulative capital investment and experience are highly correlated, so that separating their effects reliably is difficult. More important, however, is that this study continues to omit variables that may further reduce the residual productivity growth attributed to learning. Lane (1951) documents how the USMC introduced and then expanded training programs, maintained an active and sizable research department, contracted research out to numerous engineering companies and universities, and instituted numerous minor design changes. Shipyards also had active research programs and often instituted their own process innovations. U.S. Senate (1945) describes 48 new products and processes developed and implemented during 1942 and 1943, specific to shipbuilding, that were sufficiently important to merit media attention. Some of them appeared to have been suggested by shipyard workers and might well be attributed to on-the-job learning; other innovations were developed by outside suppliers of equipment and materials; in several other cases new tools were first suggested by yard workers, adopted in rudimentary form, and subsequently developed and marketed by an independent tool company. The same Senate report also documents media reports on 35 innovations in automatic welding products and techniques during the same period. Again, some were techniques developed by yard workers that one might attribute to learning. However, the most important innovations—several of which were claimed to increase welder productivity by more than 100 percent—were new machines developed entirely outside the shipbuilding industry.

It is unlikely that sufficient data will ever be available to measure the effects of these omitted variables. Even then, no doubt some of the effects should ultimately be traced to ideas developed as a result of production experience, although how much is probably an insoluble matter of semantics. One must also be careful in making general inferences from a single case study. But it does seem reasonable to draw one conclusion from the Liberty ship program that is likely to resonate elsewhere: in a case study that is widely viewed as one of the cleanest examples of learning by doing on record, the real causes of productivity growth have turned out to be more complex and more diverse than economists have long believed to be the case.

Appendix

Data Sources

Unless otherwise stated, box numbers refer to boxes in the National Archives, Records of the Office of the Historian, U.S. Maritime Commission, RG178.

A. Ship identifiers.—Hull names and USMC identifying numbers were taken from Bunker (1972, pp. 207–58). Supplementary information, particularly to track numerous name changes during the war, was taken from Sawyer and Mitchell (1985). Builders' hull numbers are contained in handwritten tabulations located in the National Archives, Records of the Production Division, U.S. Maritime Commission, various boxes, RG178.

B. Production dates.—Production times, decomposed into days between keel laying and launching, and days between launching and delivery, were taken from handwritten tabulations by G. J. Fischer, chief statistician, USMC (located in boxes 30 and 31). For each ship, either a date of keel laying or a date of delivery was taken from unattributed typescript tabulations (presumably written under the direction of Fischer, as several copies have annotations in his handwriting), located in boxes 35 and 37. Records indicate that delivery to the USMC was always made the same day the ship was made ready for delivery. Missing dates were therefore obtained by combining production times with the known dates of delivery or keel laying.

C. Monthly output.—The rate of output was constructed from the dates of keel laying and delivery. For each ship, a linear rate of production was assumed, so that the allocation of production of a ship to any given month is proportional to the fraction of total production time that fell in that month.

D. Productivity.—Direct, indirect, and total labor hours per ship were obtained from unattributed typescript tabulations located in boxes 35 and 37. These data should be uncommonly accurate. The USMC stationed auditors at each yard to calculate direct labor hours expended on each ship on a daily basis. Indirect labor was allocated to ships from weekly payroll data. No information is available on how indirect labor hours were allocated to each ship, although the methodology appears to approximate a weighted combination of production time and labor hours expended on each ship. Every two weeks, the data were compiled and submitted to the Finance Division of the USMC for reimbursement.

E. Ship quality.—Dates and severity of fractures are taken from Bates (1946) and from Board of Investigation (1945). Fracture severity is indicated by class. A class I fracture is one that either results in the actual loss of a vessel or has progressed to such an extent into the strength deck or shell as to endanger the safety of the vessel. A class II fracture is one that does not immediately place the vessel in danger but has the potential to develop into a class I fracture. Descriptions of fracture types are given in Board of Investigation (1945). Dates of war losses (by cause) are taken from Economics and Statistics Division (1946). War loss data were supplemented by information in Sawyer and Mitchell (1985).

F. Employment.—Monthly employment data are constructed from the number of direct and indirect workers, and average hours worked, contained in Bureau of Labor Statistics forms BLS 1761, Plant Operations, box 36. The data refer to employment on the fifteenth of the month. These data differ slightly from employment data tabulated in Fischer (1949). Fischer's data combine two sources, some of which report end-of-month employment and some of which report midmonth employment. Sunday shift employment data were also taken from BLS 1761.

G. Capital authorizations.—The dates, amounts, and purpose of each authorization for shipyard facilities were taken from "Statement of Facilities Contracts, Vouchers Passed for Payment, as of March 31 1946," box 56; "Facilities Allotments from Minutes Cards," handwritten tabulations, box 32; and "Major, Minor and Military Types of Vessels Constructed in 1936–1945," undated typescript, box 42. The source for these data was found damaged in the National Archives, and sheets for several large yards are missing. Detailed capital authorizations by date are available for (number of Liberty ships delivered in parentheses) Bethlehem-Fairfield (384), Calship (336), Delta (188), North Carolina (126), Oregon (330), and Todd-Houston (208). These six yards account for a little over 50 percent of all Liberty ship production.

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