HOW MUCH DID THE LIBERTY SHIPBUILDERS LEARN? NEW EVIDENCE FOR AN OLD CASE STUDY

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This paper uses previously unavailable historical records to show that several assumptions central to a learning by doing explanation of productivity growth in the construction of Liberty ships during World War II are mistaken. Impressive increases in output per worker recorded at one of the largest shipyards in the program, Calship, are shown to be strongly associated with increases in capital intensity and with a reduction in quality, where the latter is measured by the probability of a ship developing serious fractures that threatened the lives of its crew. Capital deepening and quality change, in conjunction with changes in production technologies and capacity utilization, account for virtually all the increase in labor productivity.

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Numerous empirical studies of productivity growth have shown a tendency for productivity to rise with cumulative output, particularly at early stages of production.[1] To engineers and managers, this phenomenon is known as the learning or start-up curve, but to economists it is best known as learning by doing. There is, of course, an implicit judgment in this choice of terminology that a causal relationship has been found to exist; that producers learn from experience and that cumulative production is a good measure of experience. Learning has been formally modeled in a variety of settings, and has been shown to have important consequences for market structure, development, and the appropriate design of policy.[2] Economists have, however, had no more success than psychologists in explaining *how* agents learn, and theoretical work on learning has largely been limited to analyzing the consequences of simply *assuming* its presence.

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 just be measurement error. Rosenberg (1976, p.329) has suggested that "cost reductions which have been attributed to learning by doing [may] have actually been due to other factors which have not been correctly identified, especially in cases where learning by doing has been defined as a residual." Moreover, measurement problems seem to be particularly severe in the relatively small number of classic historical studies that are regularly cited to motivate theory.[3] For example, Arrow, Arrow and Bradley (1951) and Asher (1956) have argued that the data available on World War II airframe production are too aggregated and unreliable to allow one to draw reliable conclusions about the importance of learning by doing. More

1 The list is far too large to merit selective citation here. See Dutton and Thomas (1984) and Jovanovic and Nyarko (1995) for numerous examples.

2 Again, the list is long; but among the best known are Arrow (1962), Fudenberg and Tirole (1983), Krugman (1987), Lucas (1993), and Spence (1981).

3 I have particularly in mind the studies by Wright (1936) on interwar aircraft production, by Alchian (1950) on WWII airframe production, and by Rapping (1965) on WWII merchant ship construction.

recently, Bell and Scott-Kemmis (1990) have mustered 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.[4]

But despite these doubts about the reliability of evidence drawn from wartime production experiences, there has been no attempt to show that factors other than learning can account quantitatively for the considerable productivity growth rates observed during the war. This study uses previously unavailable, and highly disaggregated, data to evaluate the reliability of conventional wisdom on the importance of learning by doing in the Liberty shipbuilding program of World War II. The paper suggests that, in this case at least, concerns about the reliability of existing evidence on learning are well founded.

The paper has two parts. The first examines three assumptions, critical to the case for a learning explanation of productivity growth in the Liberty program, and presents evidence that these assumptions are incorrect. First, capital deepening is shown to be much more important than has been assumed, and this alone can account for a substantial fraction of the observed increases in output per worker. This finding can also explain the powerful productivity-enhancing role that has been attributed to cumulative output. It turns out that cumulative output is an excellent proxy for the capital stock.

Second, the assumption that all ships were the same is not correct. Poor supervision and defective welding motivated by incentive payments for fast work resulted in over ten percent of the Liberty fleet fracturing, some disastrously so. Indeed, productivity is an excellent predictor of the probability that a Liberty ship developed fractures. Third, the assumption of constant technology is easily refuted. Construction of the first ships was well under way before the shipyards themselves had been completed, and the technology with which these ships were produced was often very different from the mass production techniques

[4] In a similar study, Lazonick and Brush (1985) have re-examined evidence on productivity growth in a 19th-century cotton mill, that David (1973) had earlier attributed to learning. They concluded that much of the growth attributed to learning may in fact have been the result of increasing labor effort induced by the exercise of managerial power over a progressively less organized labor force.

used throughout most of the war. The data show that perhaps one half of the productivity growth observed during the war can be explained by the low productivity of labor engaged in production of the first dozen ships or so.

The second part of the paper uses data exclusively from one of the largest shipyards, Calship, to decompose productivity growth by source. Increases in the stock of capital, because of time-to-build delays in yard construction and subsequent capital investment, account for a large majority of the observed increases in labor productivity. But additional sources, including changes in capacity utilization, product quality, and yard employment, also made significant contributions. Once these various sources of growth are accounted for, there is almost nothing left to be explained by learning by doing.

The layout of the paper is as follows. Section 1 reviews conventional wisdom on the Liberty ship program. Section 2 describes the Calship data. Section 3 examines capital deepening at Calship, Section 4 establishes a link between productivity growth and quality reduction, and Section 5 discusses the overlap of the yard and ship construction programs. Section 6 concludes the paper with a growth accounting exercise that strongly indicates that learning by doing does not lie behind the impressive rates of productivity growth observed at Calship.

1. The Liberty Ship Miracle[5]

In 1941, the U.S. Maritime Commission (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 2,580 ships, by far the largest ever production run of a single ship design.[6]

[5] This phrase was coined by Lucas (1993).

[6] An additional 119 vessels -- tankers, colliers, and aircraft and tank transporters -- were also classified as Liberty ships. In addition, a small number of the standard Liberty cargo ships were converted to hospital ships, troop carriers, or training ships.

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 moveable cranes to one the ways, and large whirley 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.[7] 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 twenty-four hours. There, final painting, joinery and electrical work were completed, and rigging and lifeboats were added. The same day that the 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 shipyards is primarily constrained by the number of ways at the yard, and the length of time that a ship spends on the ways before it can be launched. Modularization reduced considerably the time ships spent on the ways, greatly increasing the productive capacity of the yards. The gains in labor productivity were equally significant, as some tasks could be carried out more easily in inland work areas. For example, metal plates could be held in positions that allowed for automatic welding or that made manual welding easier.

The phenomenal increase in labor productivity experienced during the Liberty program, first brought to the profession's attention by Searle (1945), is well known. Over the course of three years, labor productivity rose at an average annual rate of 40 percent. Moreover, because yards entered the program at different times, the industry average *understates* the rate of increase in output per worker at individual yards.[8] Using data for individual yards, Searle showed

[7] Statistics and Reports Unit (1944).

that each doubling of cumulative output reduced labor hours per ship by between 12 and 24 percent.

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

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

where y_{it} is monthly deliveries in deadweight tons, A is a constant, W_{it} is the number of ways in operation at time t (his proxy for the stock of capital), L_{it} is employment in hours, and $Y_{it} = Y_{it\text{-}1} + y_{it\text{-}1}$ is cumulative yard output. Rapping estimated the parameters of the production function using pooled data from fifteen yards. His analysis confirmed Searle's earlier work. Each doubling of cumulative output was associated with an increase in output of between 11 and 34 percent (the mean of γ over six regressions was 0.23). Moreover, this apparent learning effect was robust to the inclusion of calendar time, which had no significant impact on productivity.[9] Lucas (1993, pp.259,262) has described the Liberty ship data as "the best evidence I know of that bears on on-the-job productivity change. . . . What is exceptional about the Liberty ship evidence, I think, is the cleanness of the experiment, not the behavior it documents so beautifully."

Much of this paper is concerned with an evaluation of the cleanness of the experiment. Let me make it clear, however, that this evaluation is not intended as a criticism of Rapping's pioneering analysis. Rather, the issue is that data limitations lie behind misleading inferences that have been drawn from estimates of equation (1).[10] Specifically, the evaluation focuses on three important

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8 Lane (1951) provides the most detailed graphical summary of productivity growth at individual yards.

9 Argote, Beckman and Epple (1990) have added labor turnover rates to Rapping's analysis without undermining his key findings.

10 In fact, Rapping was careful to note the limitations of his data and urged "extreme caution" in interpreting his regressions. However, his warnings have rarely been heeded in subsequent citations.

assumptions embedded in these inferences. First, that W_{it} is a good proxy for capital; second, that any changes in technology can be captured by a constant exponential trend; and third, that there are no changes in the quality of ships over time. This paper provides evidence that none of these assumptions is valid.

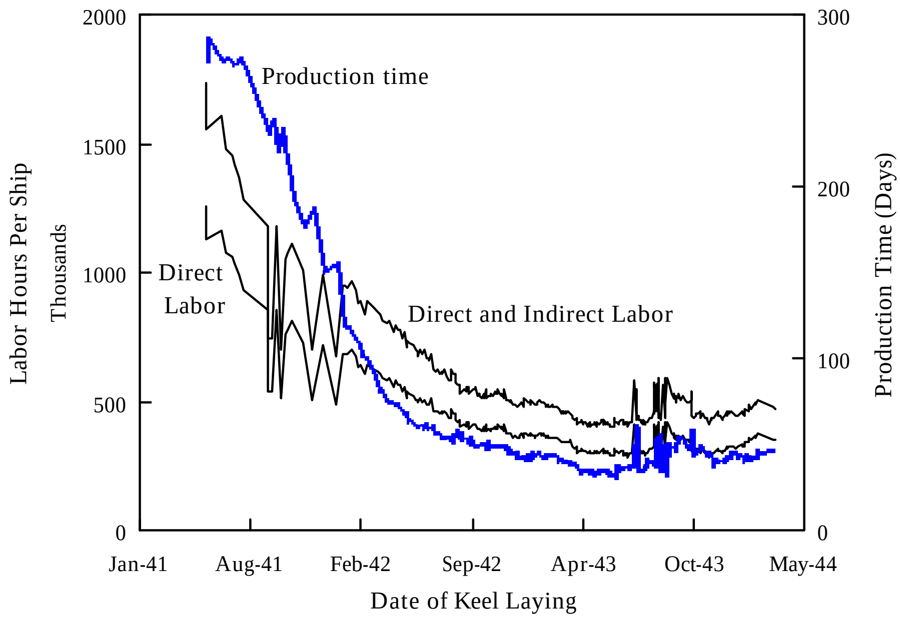
2. The Calship Data

This paper uses a new data set for one of the largest shipyards involved in the Emergency Shipbuilding Program, the California Shipbuilding Corporation (Calship) at Terminal Island, Los Angeles. The detailed data for Calship are supplemented with limited observations currently available for other yards. The data were constructed from contemporary worksheets, reports and correspondence contained in the Records of the USMC and the Records of the U.S. Coast Guard at the National Archives. Most data for Calship are disaggregated at the individual ship level.[11] Labor hours per ship are disaggregated into direct and indirect labor requirements. The dates of keel laying, launching, delivery, fractures suffered (if any), and damage due to act of war, are available for each ship. Employment data are available only monthly, but are disaggregated by type of employee, shift distribution, and weekend employment.

Figure 1 plots labor requirements and production time at Calship against the date of keel laying, and illustrates the remarkable reductions in both. Construction of the Calship yard began on 10 January 1941, and the keel of the first ship was laid on 24 May 1941 while much of the yard was still under construction. The first ship, *John C. Freemont*, was delivered 273 days later on 27 February 1942. It took 1.73 million hours of labor, and cost $3.8 million. Over the next three years, Calship constructed 336 Liberty ships, 306 of them standard Libertys and 30 of them emergency tankers. The yard was the third largest producer of Liberty ships. The last Liberty, *Martin Johnson*, was delivered on 4

11 Each yard was required to submit invoices detailing expenditures on each ship to the Maritime Commission every fifteen days. To assist in the accounting process, the Commission employed resident auditors at the yard. Productivity data are taken from worksheets constructed from these audited accounts.

Figure 1. Pro*ductivity at Calship*



Sources: Production dates from handwritten tabulations located in Records of the Production Division, various boxes. Production time from handwritten tabulations by G.J. Fischer, Chief Statistician, located in Records of the Historian's Office, Boxes 30 & 31. Labor requirements are from unattributed typescript tabulations, located in Records of the Historian's Office, Boxes 35&37 (Records of the USMC, National Archives RG 178).

May 1944. It took 48 days and 474,857 labor hours to build, and cost the Maritime Commission $2.7 million. The last ship to be produced did not set production records at the yard. In fact the record had been set a year earlier by *Finley Peter Dunne*. Delivered on 30 June 1943, it took 406,000 hours of labor and 31 days to build. Calship also delivered 131 other types of ships, primarily Victory cargoes. But until April 1943, the yard built nothing but standard Libertys.[12] As Table 1 shows, Calship's experience was typical of the larger yards.

[12] Figure 1 also shows two periods of abnormal volatility in productivity at Calship. The first, late in 1941, will be shown in Section 5 to be caused by variations in production techniques resulting from the production of ships while the yard itself was still under construction. The second, in mid-1943, identifies the production dates for the 30 emergency tankers.

Table 1. *Production Characteristics of the Four Largest Yards*

	Calship	Richmond #2	Bethlehem Fairfield	Oregon
Production Numbers:				
Liberty ships	336	351	284	330
Others	131	89	124	133
Number of ways[a]	16	12	16	11
Labor Hours (thousands):				
First ship	1,735	1,164	1,199	1,058
Last ship	475	352	465	530
Record	406	302	412	294
Production Time (Days)				
First ship	273	159	244	253
Last Ship	48	27	40	25
Record	31	7[b]	28	20

[a] At peak production.

[b] A publicity stunt produced under exceptional circumstances. The next fastest took 25 days.

Sources: See notes to Figure 1.

3. Capital Deepening

The absence of data on capital has encouraged a perception that none of the massive increases in productivity at the yard level can be attributed to the familiar mechanism of capital deepening. Rapping (1965) and Argote, Beckman and Epple (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. However data on physical infrastructure at each yard suggest that the number of ways is indeed a crude proxy.

Table 2 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 14,200 square feet to 66,400 square feet per way. It is also evident that the four yards with above average productivity had significantly more infrastructure than the three least productive yards.

Table 2. *Selected Facilities per Way for 8 Yards*

	Crane Capacity (tons per way)	Machinery and Equipment (thousand dollars per way)	Prefabrication Plant (square feet per way)
A. Four yards with above average productivity in 12th round			
Calship	34.3	679	27.7
N. Carolina	44.7	765	30.2
Oregon	46.5	689	66.4
Permanente	40.0	593	53.7
4-yard average	41.4	682	44.5
A. Three yards with below average productivity in 12th round			
Bethlehem-Fairfield	34.0	811	33.4
New England	22.4	579	17.2
Todd-Houston	24.7	286	32.7
3-yard average	27.0	558	27.7

Source: Fischer (1948, Table 1).

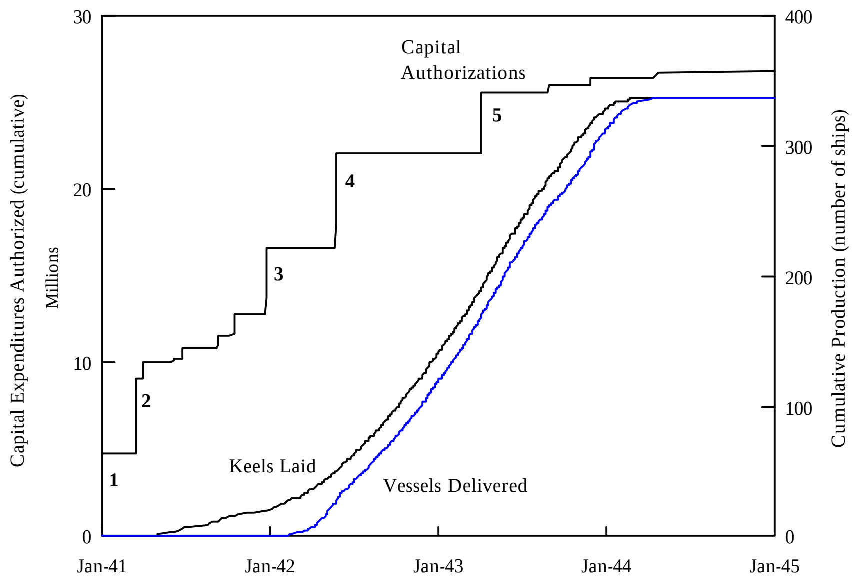
Of course, these differences across yards do not by themselves suggest that differences in capital per way might account for any of the increase in productivity over time. However it is evident that not all investment was carried out at the time the yards were constructed. USMC (1945, p. 4) notes, for example, that no new shipyards were established during the fiscal year July 1943 - June 1944, but $31,142,777 were expended during that period for additional facilities in existing yards, none of which was used to contruct additional ways.

Figure 2 plots Maritime Commission authorizations for capital investments at Calship along with cumulative output. On 10 January 1941, the Commission approved expenditures of $4.8 million to build six ways and supporting production facilities, adding on 10 April another eight ways and supporting facilities for an anticipated cost of $4.3 million. These expenditures account for only one third of total investment during the program. On 16 January 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 nineteen keels had been laid, and five ships had been launched. On 16 June 1942, another $1.9 million was approved to installnew whirley cranes that would enable the yard to pre-assemble larger components, and to install additional welding equipment on ways and pre-assembly platforms. Fifty keels had already been laid prior to this investment. Additional authorizations, between May 1941 and January 1943, accounted for a further $8.2 million expansion of capital. Finally, $4.7 million of new capital expenditures were authorized in April 1943 to facilitate conversion of the yard to production of the more complex, and heavier, Victory ships.

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.[13] However, the evidence clearly indicates that all major incremental investments were direct and immediate responses to unanticipated increases in the scope of the Emergency Program. Lane (1951, pp.40–71)

[13] Indeed, Vice Admiral Vickery, vice-chairman of the USMC, testified to Congress that additional capital expenditures were often a result of "everybody thinking of something new they wanted . . . like the youngster with candy who wants more." (House of Representatives, 1943, p.912). Lane (1951, p.473), noting possible inter-yard spillovers on 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."

Figure 2. *Capital Deepening at Calship, 1941-1945*



Notes on major authorizations: 1) Construction of 8 ways and supporting facilities. 2) Construction of additional 6 ways and supporting facilities. 3) Additional buildings for prefabrication plant, and expanded electrical and automatic welding facilities. 4) Larger capacity cranes on ways, and additional welding equipment on ways and pre-assembly platforms. 5) Facilities upgrading, primarily to assist conversion to Victory ship program.

Sources: See notes to Figure 1. Capital authorizations from untitled typescripts, Records of the Historian's Office, Boxes 32 and 44 (Records of the USMC, National Archives RG178).

documents the series of expansions in the scheduled production of Liberty ships that took place in 1941 and 1942. On 3 January 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 27 March 1941, Congress approved the Defense Aid Supplemental Appropriation Act, which provided funds to construct an additional 200 ships for the British. A contract with Calship, dated 17 April 1941, called for an additional 24 ships. The Japanese attack on Pearl Harbor on 7 November 1941 immediately generated another wave of expansion as the United States entered the war. On 16 January 1942, Calship won a contract for an additional 109 ships. Finally, unexpected heavy losses to torpedo attacks in the Atlantic during Spring 1942 generated a new round of contracts in June of that year, with Calship contracting for 60 more ships on 16 June 1942.

These new and unanticipated contracts for ships clearly coincide with the capital expansions at Calship. But there is also 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]."[14]

Capital deepening at Calship over the life of the Liberty program was extensive. Although investment decisions did not arise from the gradual identification of capital constraints on production, cumulative output nevertheless turns out to be an excellent proxy for capital. The correlation between the logarithm of cumulative capital authorizations and the logarithm of cumulative output at Calship is 0.91, while the correlation between calendar time and the logarithm of cumulative capital authorizations is significantly lower, at 0.72.[15] Thus, point estimates of the coefficient on cumulative output obtained from OLS regressions of a log-linearized version of equation (1) correspond fairly precisely to

[14] Both quotes from untitled typescripts containing summaries of USMC minutes, Schmelzter's dated 18 January 1942 and Flesher's dated 11 June 1942. Records of the Historian's Office Box 32, Records of the US Maritime Commission (National Archives, RG178). Almost identical justifications accompany requests for, and approvals of, additional facilities at Todd-Houston (Vickery, 1943a), Jones-Brunswick (Vickery, 1943b), and Oregon (Oregon Shipbuilding Corporation, 1942, p.1).

[15] The predictive power of cumulative output is likely to extend across yards. Lane (1951, p.145) points out that when new capital expansions and ship contracts were being considered, "the Maritime commission turned to the West Coast . . . because of its outstanding record." Shipyards were more likely to win additional contracts if they had already produced ships at an above average rate.

the elasticity of output with respect to capital.[16]

This explanation for the apparent robustness of the learning effect mirrors findings from Sinclair, Klepper and Cohen's (1997) study of the specialty chemicals division of a modern Fortune 500 company. They found that variations in learning rates across more than one thousand products were largely attributable to variations in process R&D. Moreover, they established that cumulative output was an excellent predictor for future output and hence for the expected returns to R&D. Products with greater cumulative output were therefore more likely to be the recipients of R&D effort, and more likely to exhibit cost reductions.

4. Fractures in Liberty Ships

Just as the peak productivity levels were being recorded in the winter of 1942-1943, some remarkable hull failures occurred. On 16 January 1943 a Liberty tanker, *Schenectady*, split in two while moored in calm water at the outfitting dock at Swan Island, Oregon.

> 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.
>
> US Coast Guard (1944)

The ship was twenty four hours old.

The *Schenectady* was not the first Liberty ship to fracture, although it was certainly one of the more dramatic cases. In fact ten ships, eight of them standard Libertys, had already suffered a class I fracture by the time of the

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[16] Estimating equation (1) with the Calship data yields a coefficient of 0.30 on the logarithm of cumulative output. Replacing cumulative output with cumulative capital authorizations, the corresponding point estimate is 0.34.

Schenectady incident.[17] But it was the first to happen in full view of a city of half of a million people, and hence the first to attract widespread attention. Portland newspapers of 17 January 1943 reported the story, and publicity about several more serious casualties in the months following could not be suppressed.[18] On 2 February 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.

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 June 1946, 103 Liberty vessels had suffered one or more class I fractures, and another 291 had suffered at least one class II fracture.[19] By the end of the war, over fifteen percent of the Liberty fleet had suffered fractures that caused total loss or required extensive and costly repairs. At Calship, 63 of 306 standard Liberty ships eventually produced fractures, nineteen of them class I fractures.

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17 A class I fracture is one which results in either the actual loss of a vessel, or which has progressed to such an extent into the strength deck or shell as to endanger the saftey of the vessel. Descriptions of class I fractures are given in Board of Investigation (1945).

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

19 A class II fracture is one which does not immediately place the vessel in danger, but which has the potential to develop into a class I fracture. Some vessels fractured as many as five times, and there were in fact over one thousand fracture incidents. Fractures known to have occured before 2 February 1946 are taken from Bates (1946) and Board of Investigation (1945).

Following the *Schenectady* incident, the Maritime Commission established a Board of Investigation to study the causes of, and provide solutions to, the problem of fracturing. The Board immediately funded over thirty distinct research projects at laboratories and universities throughout the country. There is much talk in the interim reports of the Board of Inquiry[20] 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, and that were "relieved" by the crackings. But, as Lane (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 this uncertainty, the major research effort funded by the Board generated numerous important design changes between February and April 1943, which are described in some detail by Lane (1951, pp. 548-550) .[21]

While experts were talking about locked in stresses, they were also paying much attention to the quality of welding.[22] In fact, by the time that Tyler (1947) surveyed the fracture problem, the problem of welding quality had become a central theme.[23] Defective welds were associated with expanded use of automatic welding machines in late 1942, which reduced the strength of critical welds and joints.[24] But C.E. Wilson, Production Vice-Chairman of the War Production Board, clearly believed as early as March 1943 that poor welding was due to much more than 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.[25]

[20] Especially in Board of Investigation (1944).

[21] Additional modifications were mandated in January and February 1944.

[22] In fact, the official Coast Guard report attributes the *Schenectady* incident to welds in critical seams that "were found to be defective."

[23] Half of Tyler's report is devoted to the topics of welder training, supervision, and welding practices.

[24] *Marine Engineering and Shipping Review* (1942) reported that yards were introducing new automatic welding techniques that increased production by up to 100 percent.

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 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"[26] and, being a minor, was sentenced to eighteen 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 substituted test plates made by others, while 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 had encouraged greater production speed with the full knowledge that reliability might suffer as a consequence. For example, the American Bureau of Shipping, the agency reponsible for coordinating safety inspections, issued a statement in early 1942 that explicitly directed 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.[27]

Tyler (1947, p.18) notes that the letter was discussed without adverse comment in a meeting of the Production Division of the USMC.

While contemporary documents clearly link the push for rapid production to the quality of work, little more than anecdotal evidence exists. Table 3

[25] Lane (1951, pp.544-573) and Tyler (1947) report several of Wilson's anecdotes.

[26] Wilson, quoted in Tyler (1947, p.72).

[27] Quoted in Tyler (1947, p.17).

provides estimates of the relationship between labor productivity and the probability of a vessel produced by Calship eventually suffering one or more fractures. The first column reports the results of a probit analysis, while the second column contains the coefficients of a duration model in which the hazard rate has a Weibull distribution. The regressions control for the fact that the observation for each ship is truncated, either by the sampling date of 2 February 1946, or because the ship's war service was ended at an earlier date due ot war loss.[28] In the probit model an increase in the length of war service is expected to increase the probability of a fracture. The coefficient on a dummy variable to capture the effect of the design changes imposed on all yards by May 1943 is expected to be negative in both regressions.[29] All coefficients are significant and have the expected sign. In particular, a reduction in labor hours expended on the production of a ship is strongly associated with an increase in the probability that it subsequently developed fractures. Moreover, this relationship is robust to the inclusion of calendar time. The same results hold when production order (hull number) is also included, when labor hours and the sampling window enter in logarithms, when total labor hours are used instead of direct labor hours, and when the binary model is estimated by logit.

Incidentally, Tyler (1947) reports that it was widely believed during the war that fracture rates were unrelated to the length of time a ship had been in service. The point estimate of the parameter v in the duration model is not significantly different from one. Thus, the Weibull model cannot be distinguished from an exponential model with a constant hazard rate, lending formal support to that belief.

[28] Data on war losses are from Economics and Statistics Division (1946) and Sawyer and Mitchell (1970).

[29] As Calship laid only two more Liberty keels after February 1944, no dummy is used for the second round of mandatory design changes.

Table 3. *Determinants of Fracture Probabilities and Hazard Rates in Standard Liberty Ships Produced at Calship*

	PROBIT $y_i = 1$ IF FRACTURE REPORTED BY 2 FEB 1946, 0 OTHERWISE	DURATION MODEL WEIBULL[d]
CONSTANT	1.25	4.76
	(1.6)	(2.6)
DIRECT LABOR HOURS PER SHIP (millions)	−5.18**	−10.53**
	(1.8)	(3.5)
WAR SERVICE[a] (years)	0.46**	____
	(.17)	
DESIGN CHANGES[b] (dummy)	−0.70*	−1.29*
	(.31)	(.54)
DATE OF KEEL LAYING (hundreds of days since first keel laid)	−0.18	−0.48*
	(.14)	(.24)
v	____	0.90[e]
		(.17)
NO. OF OBSERVATIONS[c]	306	306
LOG LIKELIHOOD	−130.8	−204.9

Asymptotic standard errors in parentheses. * Significant at 5% level. ** Significant at 1% level.

[a] Years from delivery to end of sampling period on 2 Feb 1946 or war loss, whichever comes first.

[b] Dummy variable: 0 if keel laying before May 1943, otherwise 1.

[c] The 30 tankers are excluded.

[d] The hazard function of the Weibull model is $\lambda_i(t) = \lambda_i v (\lambda_i t)^{v-1}$, where $\lambda_i = \exp(\mathbf{b}'\mathbf{x_i})$ and $\mathbf{x_i}$ is a vector of the regressors. The log-likelihood function is

$$\ln L = \sum_i [\delta_i (v(\ln s_i + \mathbf{b}'\mathbf{x}_i) + \ln v) - \exp(v(\ln s_i + \mathbf{b}'\mathbf{x}_i))],$$

where $\delta_i = 1$ if the vessel developed fractures, and $\delta_i = 0$ otherwise; s_i is the time (in years) between delivery and whichever comes first among fracture date, war loss and end of sampling period. See Green (1993, pp. 716-722).

[e] Not significantly different from 1.

Figure 2. *Predicted Fracture Probabilities at Calship*

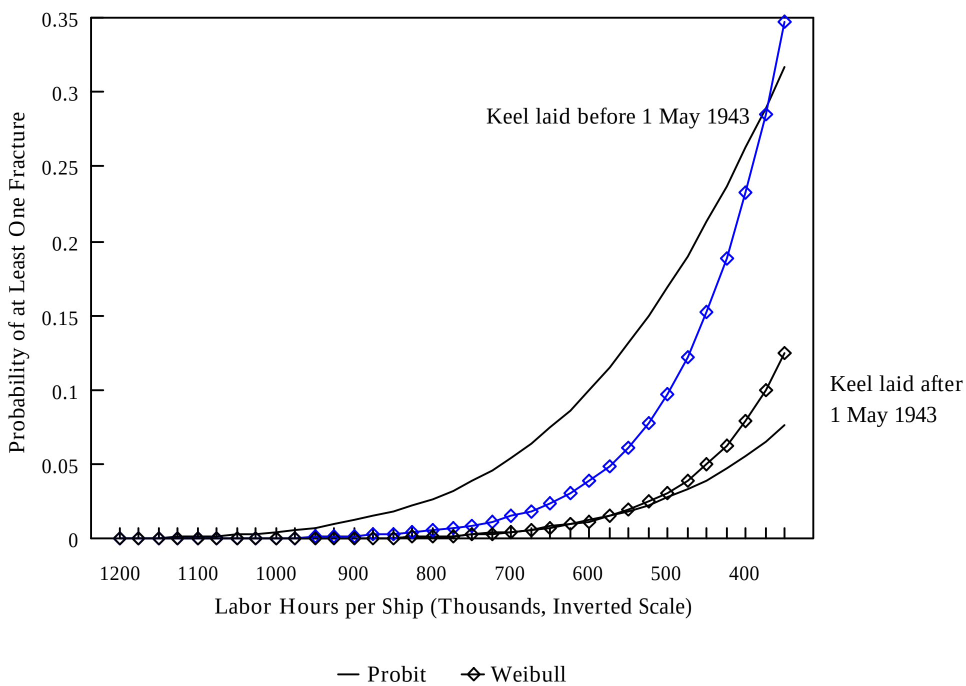

Figure 2 plots the predicted probabilities of a fracture for the range of labor requirements observed in the data, and highlights the similarity between the two sets of results. For the probit regressions, the length of war service is held at its sample mean of 2.5 years, while for the duration model the figure plots the probabilities that the survival time is less than 2.5 years. Predictions are produced separately for ships produced before and after the mandatory design changes of May 1943. For ships whose keels were laid before May 1943 the observed reduction in direct labor requirements, from 1.25 million hours to 350,000 hours, increased the probability of a fracture from zero to almost one third. The design changes mandated in the spring of 1943 significantly reduced the risk of fractures. Holding constant war service (2.5 years) and direct labor requirements (350,000 hours), the design changes reduced the probability of fractures from one third to about 0.1.

5. Time-to-Build Delays

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. 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, 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 were ships produced after the yard was completed, and labor productivity was lower.

There are no direct data on how long it took to construct a new yard, nor on how many ships were affected, but both were clearly substantial. In August 1942, for example, Vickery testified to congress 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" (House of Representatives, 1942, p.251). If this was generally true, productivity on the first nineteen ships produced at Calship 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[30] provide some illustration. The yard laid its first Liberty ship keel on 24 September 1941, yet on 7 January 1942 only five of seven cranes in the construction plans had been delivered and only three of these were operational. Four ships were being constructed at the time, and two of them were being constructed largely from manual welding.[31] Clearly, the technology

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[30] After a management change, the yard subsequently changed its name to the New England Shipbuilding Corporation.

[31] The information is contained in attachments to Allen (1942), who commented in a

of production was different for the first round of the ways, and it would be wrong to attribute to learning by doing 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 productivity comparisons.

There are no new data for Calship that might allow us to measure time-to-build delays. Hence, it will be necessary in the next section to follow Lane and disregard productivity data for some of the earliest ships produced. Figure 1 provides some insight as to where that cutoff should be made. Labor productivity on successive keels was abnormally volatile until the twenty-first keel was laid on 29 January 1942, from which date productivity on new ships began to rise more or less monotonically. It seems reasonable to infer that until late in January 1942 some ways had only restricted access to the prefabrication facilities, while other ways had normal access. This conclusion finds further circumstantial support from the sudden drop in production time after the twenty-first keel had been laid. The twentieth keel was laid on 14 January 1942 and was delivered 157 days later. The twenty-first keel was laid just two weeks later, but was made ready for delivery in only 119 days. The decline in production time was the largest in absolute terms between successive keel layings and, at over 24 percent, was also by far the largest proportional decline. In the next section, we will therefore attribute the gain in productivity observed between the first and twenty-first ships (a period of approximately one year) to time-to-build delays, and eliminate the first score of ships from subsequent analysis.

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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."

6. Sources of Productivity Growth at Calship

This section concludes the paper with a decomposition of productivity growth at Calship among the various sources discussed in previous sections. To do so, it is necessary to transform capital authorizations into utilized capital stock estimates, and to transform fracture probabilities into labor hour equivalents. Direct evidence to facilitate these tasks is scarce, and we will have to rely on some creative guesswork.

The construction of a capital services series involves two adjustments to the raw data on capital authorizations. First, time-to-build delays will make the actual capital stock smoother than is indicated by capital authorizations. I assume that physical investment begins ten days after an authorization, and the creation of productive capital proceeds at a constant rate equal to $1 million dollars of new infrastructure per month.[32] Second, to adjust for variations in capacity utilization, I assume that capacity utilization is 100 percent when the yard operates on a seven-day, three-shift production schedule. Monthly data on shift and weekend employment are then used to provide an estimate for monthly capacity utilization rates, under the additional assumption that employment in each month on the first shift on weekdays represented capacity at that time.[33]

The following assumptions are used to transform fracture probabilities into labor hour equivalents. I assume that the cost of a class I fracture is the loss of two months (out of an average of 2.5 years) of ship service time, plus 150,000 labor hours in repair. A class II fracture is assumed to cost the loss of one month of service time and 50,000 labor hours of repair.[34] In both cases, the

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[32] These figures are a little more conservative than the time-to-build delays suggested from the evidence on yard construction.

[33] When ship production declined late in the war, employment was reduced first by ending weekend work, and then second and third weekday shifts, before reducing employment on the first shift.

[34] From Lane's (1951) descriptions of the damage caused by fractures, these numbers seem moderate. However, the contribution of quality change to productivity growth turns out to be quite small, and the results of the growth accounting excercise reported below are not sensitive to wide variations in these numbers.

labor cost of lost service for a fractured ship is calculated using the labor hours required in the production of that ship. Labor productivity can then be adjusted for quality by weighting the labor cost of each type fracture according to the shares of class I and II fractures in Calship's 63 fractures, and multiplying the weighted sum by the predicted probability of a fracture appropriate for a vessel with the indicated labor requirement. The probabilities are taken from the probit regression.

The following log-linear specification is modeled:

(2) $$\ln q_i = \beta_0 + \beta_1 \ln k_i + \beta_2 \ln L_i + u_i,$$

where q_i is total labor hours expended on ship *i*, adjusted for quality; k_i is the capital stock available when the keel of the *i*th ship was laid, adjusted for capacity utilization; L_i is total employment hours during the month in which keel *i* was laid; and u_i is a disturbance. Equation (2) can, of course, be derived from a Cobb-Douglas production function; the expected signs of the coefficients are $\beta_0 > 0$, $\beta_1 < 0$, and $\beta_2 > 0$.

Measurement errors in quality and in the capacity-adjusted capital stock may cause serious problems for consistent estimation of (2). Valid instruments for quality are not available, and so the dependent variable has been adjusted for quality directly. Neither k_i nor L_i were used in the probit and Weibull regressions, and it is reasonable to conclude that measurement error in q_i is uncorrelated with the regressors in (2). Any measurement error in quality will show up in the disturbance term and possibly in a biased constant term. This will have an effect only on the correct measurement of the contribution of changes in quality to measured productivity growth. Fortunately, valid instruments for the capital stock are available. It has already been observed that yards which had produced more ships and had more experience were more likely to receive additional capital. Hence, calendar time and cumulative production will be correlated with the unobserved true capital stock, but not with the measurement errors introduced by the time-to-build delays that have been assumed.

The results of the regression analysis are in Table 4. As discussed earlier, all productivity growth in the first twenty ships is attributed to time-to-build delays in yard construction, and the sample excludes these ships. Column (1) reports OLS estimates, while column (2) reports the parameter estimates from instrumental variable (IV) estimation. The coefficients are all significant and have the expected sign. Constant returns to scale require that the sum of the coefficients on capital and labor sum to zero, which is easily rejected. In fact, returns to scale are estimated to be close to two.[35] A one percent increase in capital at the Calship yard reduced labor hours per ship by an average of 1.6 percent, while a one percent increase in employment increased labor hours per ship by an average of 0.6 percent.

Note in both cases, however, the presence of significant serial correlation. Augmented Dickey-Fuller tests for stationarity strongly indicate that q, k, and L are all I(0), and hence the low Durbin-Watson statistics are assumed not to be a sign of a spurious regression. Column (3) thus reports the results of IV estimation with a correction for first-order serial correlation in the residuals. The residuals are stationary, but the high autocorrelation coefficient does give warning that shocks to productivity that are omitted from equation (2) have effects that decay rather slowly.

The parameter estimates from column (3) were used to account for the sources of productivity growth at Calship. Figure 3 plots the results of decomposing productivity growth into the cumulative contributions of: 1) time-to-build delays in yard construction; 2) quality changes; 3) changes in the capital stock; 4) changes in employment; and 5) an unexplained residual.

Estimating the contribution of time-to-build delays in yard construction is straightforward given the assumption that productivity growth for the first twenty ships is entirely attributable to this source. As Figure 3 indicates, time-to-build delays account for a 45 percent reduction in hours per ship during the first year. Thereafter, of course, its contribution is constant.

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[35] For an equivalent specification to (2), Rapping (1965) had estimated returns to scale of about 1.75.

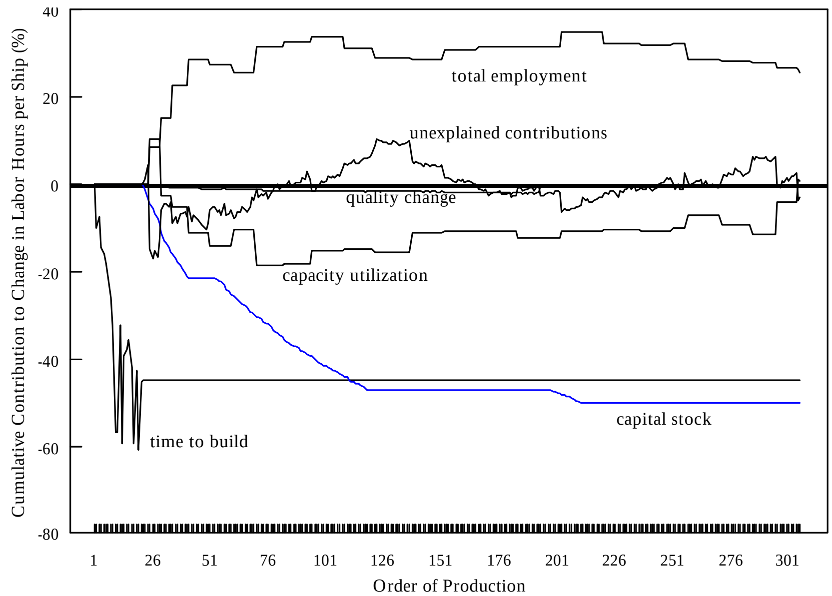
Table 4. *Estimates of Productivity Equation*

DEPENDENT VARIABLE: LOG OF QUALITY-ADJUSTED LABOR HOURS PER SHIP, $\ln q_i$			
	(1)	(2)	(3)`
	OLS	IV	IV–AR1
CONSTANT	2.819	3.745	3.570
	(.15)	(.12)	(.79)
$\ln k_i$	−1.264	−1.655	−1.620
	(.06)	(.05)	(.31)
$\ln L_i$	0.166	0.488	0.611
	(.05)	(.06)	(.29)
ρ	____	____	0.91
			(.04)
OBSERVATIONS	286	286	285
ADJUSTED R^2	0.81	0.78	0.96
DURBIN WATSON	0.15	0.17	2.30

Standard errrors in parentheses. Columns (1) and (2) have robust standard errors. Columns (2) and (3) use the logarithms of cumulative output and the date of keel laying as instruments for the capital stock. Column (3) adjusts for first-order serial correlation using Cochrane-Orcutt; ρ is the estimated coefficient on the lagged disturbance. Augmented Dickey-Fuller tests for stationarity yield test statistics of –5.23 for $\ln q_i$ –5.02 for $\ln k_i$, and –6.86 for $\ln L_i$. The 1 percent critical value is –3.51, and the unit root is easily rejected in all three cases.

The estimated contribution of quality changes, in contrast, is rather small. As the probability that a ship develops fractures rises, so does the discrepancy between observed and quality-adjusted labor requirements. However, the expected cost of fractures is never greater than 3 percent of the initial labor requirements. After the mandatory design changes that were introduced in spring 1943, about the time that hull number 180 was laid, the cumulative contribution of quality change suddenly drops, to less than 0.5 percent of the observed

Figure 3. *Sources of Productivity Growth at Calship*



productivity growth. This estimate is, of course, dependent on the assumptions made about the cost of fractures. Nonetheless, it is clear that no plausible cost estimates will change the conclusion that the contribution of quality changes was, despite the dramatic nature of the fracture incidents, rather small.

As one might expect, the largest contributors to productivity growth are the increases in the capital stock, aided by increases in capacity utilization for the first hundred ships, and partially offset by increases in yard employment. By the end of the Liberty ship construction program, capital investment had accounted for a 70 percent reduction in labor requirements, employment increases had caused a 30 percent increase in labor hours, while the terminal contribution of capacity utilization was zero.

Finally, Figure 3 also plots the unexplained contributions. On average, about 5 percent of the observed reductions in labor requirements remain unexplained. At worst, the growth decompositions leave only 10 percent unexplained. The serial correlation identified in the residuals of equation (2) is quite evident, and may result from omitted productivity shocks that have fairly slow decay rates. [36] Nonetheless, the magnitude of any omitted shocks appears to be rather small. Above all, the growth accounting exercise has left no room for learning by doing.

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[36] One possible candidate for the positive residuals in 1942 is the shortage of steel documented by Lane (1951, pp. 311-352). While there was a widepread belief that steel shortages in 1942 had a deleterious effect on productivity, available data on steel inventories are incomplete and insufficient to test the proposition.

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