LEARNING BY NECESSITY:

GOVERNMENT DEMAND, CAPACITY CONSTRAINTS, AND PRODUCTIVITY GROWTH

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Abstract

This paper studies how firms adapt to demand shocks when facing capacity constraints. I show that increases in government purchases raise total factor productivity in quantity units at the production-line level. Productivity gains are concentrated in plants facing tighter capacity constraints, a phenomenon I call "learning by necessity". Evidence is based on newly digitized archival data on US World War II aircraft production. Shifts in demand across aircraft with different strategic roles provide an instrument for aircraft demand. I show that plants adapted to surging demand by improving production methods, outsourcing, and combating absenteeism, primarily when facing tighter capacity constraints.

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1 Introduction

How do firms satisfy increased demand for their products when facing tight capacity constraints? The conventional answer is that they can't because demand has no effect on firms' productivity. An alternative view posits that firms can increase productivity when facing demand shocks and that high demand induces innovation that circumvents capacity constraints. This is a common interpretation of the performance of the US economy during the Second World War: Although the US was close to full employment by the time Pearl Harbor was attacked, munitions production nevertheless surged at declining production costs. This observation also spurred post-war research on *learning by doing*: a term that encompasses the many ways plants improve productivity with experience. This work has been extremely influential, fostering a literature on learning by doing (see Thompson 2012, 2010 for reviews) and endogenous growth (Romer 1986, Lucas 1988, 1993).

However, existing empirical work on this topic has some limitations. It has mostly skirted the identification challenge of differentiating whether increased demand, production, and experience lead to higher productivity, or vice versa. I show that this is not merely a theoretical concern but rather that traditional learning-by-doing (LBD) regressions show substantial pre-trends and clear indications of reverse causation. Further, while the focus has often been labor productivity, Thompson (2001) shows the importance of capital in evaluating learning by doing, and Basu *et al.* (2006) demonstrate the importance of capital utilization in measuring productivity over the business cycle. Thompson (2010) notes that the the concept of the "experience curve" is vague: whether productivity gains are passive or driven by active responses to higher demand. Finally, most learning-by-doing studies give static estimates of the experience curve. This is an important drawback: I show almost no contemporaneous effect on productivity, with effects peaking only after a year.

In this paper, I address some of these shortcomings. I utilize detailed archival data on US aircraft production during World War II, including previously untapped measures of physical capital and capital utilization, essential for evaluating total factor productivity (TFP). I address the identification challenge with an instrumental variable. I use the national output of broad aircraft types in each month as a ("leave one out") instrument for aircraft demand in each production line in that month. True, procurement was channeled to plants the military and government expected most likely to deliver aircraft rapidly, *within* broad aircraft types (e.g. which plant should deliver fighter aircraft). However, as outlined in Section 3.3, the allocation of national procurement *across* these broad aircraft types (e.g. the decision of whether to buy more fighter or bomber aircraft) was driven by external factors such as military strategy, combat losses, and battlefield circumstances.

Using a two-way-fixed effects Local Projections Instrumental Variables estimator, I plot the dynamic response of productivity to aircraft demand. I observe a negligible immediate impact on productivity. Instead, I find a delayed response of 0.4% growth in quantity-based, and capital-utilization adjusted, Total Factor Productivity (TFPQ) within 12-months of a 1% demand shock.

I then investigate the role of capacity constraints on the learning curve. I illustrate in a simple model why firms facing capital and labor adjustment costs and convex utilization costs are induced to adopt new production techniques when demand surges. Critically, convex utilization costs mean that technology adoption incentives are greater under tighter capacity constraints, as plants operate on steeper portions of their cost curves. Hence productivity responds more to demand (learning curves are steeper) when plants are already operating at high utilization. I refer to this phenomenon, where increased demand confronts limited production capacity and leads to productivity growth as *Learning by Necessity*. Indeed, I show that plants with higher capacity utilization rates see 80% higher productivity growth in the year following a demand shock. I measure capacity constraints using several separate indicators, all based on new archival data: capital utilization derived from shift-utilization data; labor utilization (weekly hours per worker); high-wage labor markets; and the War Manpower Commission's classification of labor markets by tightness.

Finally, I document several active measures taken by plants to increase productivity. First, production methods in the aircraft industry changed dramatically during the war. The most prominent improvement was the move from job-shop (custom and nearly handmade) production methods to production line methods (standardized products, interchangeable parts, smaller tolerances). Utilizing newly collected data from historical news sources and firms' annual reports, I present suggestive evidence that plants that gained high experience were more likely to adopt new production methods, but only if they were high utilization plants. Second, the airframe industry moved from mostly in-house production to greater reliance on outsourcing and subcontracting, and I find greater such reliance in capacity-constrained plants facing demands shocks. Third, management made concerted efforts to improve working conditions and worker morale, to reduce absenteeism and turnover. I use newly digitized archival data on absenteeism to show that plants with higher labor utilization lost *fewer* labor hours to absenteeism in response to demand shocks.

Previous research has documented learning by doing in aircraft (Wright 1936, Middleton 1945, Asher 1956, Alchian 1963, Rapping 1965) and shipbuilding (Searle 1945 Thompson 2001) industries. These estimates were based on correlations, lacking a causal interpretation. Recent studies have proposed instruments for experience: Benkard (2000) uses lags of global GDP and oil prices as instruments and Levitt *et al.* (2013) use the experience of one production line as an instrument for another in the same plant. Both studies are for a single plant rather than an entire industry and the latter measures production defects rather than labor productivity. Neither controls for capital or its utilization, nor do they provide dynamic estimates that control for lagged demand, which I show to be important in uncovering the causal impact of demand on productivity. Most importantly, this paper is the first to document how learning by doing interacts with capacity constraints: learning by necessity.

An extant macroeconomic literature has estimated returns to scale in industry-level production functions (Hall 1990, Burnside 1996, Basu & Fernald 1997). Existing learning by doing estimates typically ignore returns to scale. Estimates of returns to scale typically assume that demand cannot affect productivity. I provide a framework that nests the two and separate the effect of demand on productivity from static returns to scale. A literature in international trade emphasizes the importance of market size on productivity and innovation (Acemoglu & Linn 2004; Finkelstein 2004 De Loecker, 2007, 2011; Atkin *et al.* 2017 Melitz & Redding 2023). But these focus on the long-run, not business cycle frequency, and don't speak to the importance of capacity utilization.

The notion that demand may affect productivity is implicit in the endogenous growth literature and more explicit in the literature on induced innovation (Romer 1987, Newell *et al.* 1999, Popp 2002). Recent work has further posited that cyclical demand could spur productivity through similar channels (Benigno & Fornaro 2018, Moran & Queralto 2018, Anzoategui *et al.* 2019, and Jordà *et al.* 2020). In an early contribution, Hickman (1957) posited that high utilization could lead to capital investment incentives, what he called "the acceleration princple". Arthur (1989) outlined a theoretical non-linear relationship between technology adoption and demand. In a case study of a single aircraft plant in World War II, Mishina (1999) documents high turnover rates and therefore views experience as a less plausible explanation for productivity growth in the plant. Instead he suggests a phenomenon of "learning by stretching," a precursor to the concept of "learning by necessity" of this paper.

There is a voluminous literature studying the effects of government purchases on the economy, and military spending has been used to identify government spending shocks (Barro 1979, Ramey & Shapiro 1998, Barro & Redlick 2011, Ramey 2011a,b, 2016, 2019, Nakamura & Steinsson 2014, Chodorow-Reich 2019, Auerbach *et al.* 2020). Unlike the extant literature, this article doesn't focus on the aggregate effects of public expenditures on GDP, private consumption, or unemployment (the fiscal multiplier), but rather on its effects on productivity and its dependence on capacity utilization. Antolin-Diaz & Surico (2022) show that the effects of aggregate US military spending are long-lived and that it stimulates innovation and private investment, consistent with the mechanisms studied here. Brunet (forthcoming) uses Wold War II procurement data to study the effects of government spending on output and employment using state-level variation. This paper also speaks to the debate on the dependence of fiscal multipliers on the degree of slack in the economy (Auerbach & Gorodnichenko 2012, 2013, Owyang *et al.* 2013, and Ramey & Zubairy 2018), and to Boehm & Pandalai-Nayar's (2022) finding that supply curves are convex. A large literature has studied the longer-run impact of World War II public spending (Rhode 2000, Fishback & Cullen

2013, Jaworski 2017, Hanlon & Jaworski 2021). Rockoff (2012) and Fishback & Jaworski (2016) give broader reviews of the literature on the impacts of World War II on the post-war economy.

Finally, the paper relates to a literature on capacity utilization, its response to demand shocks, and as a confounding factor in productivity measurement (Burnside & Eichenbaum 1996, Basu *et al.* 2006). This paper shows that TFPQ grows in response to demand shocks (and is procyclical) even controlling for increased utilization, with real productivity gains, not merely reflecting mismeasurement. Additionally, plants with high rates of utilization see relatively higher productivity growth when faced with rising demand, indicating a richer interaction between the business cycle, capacity utilization, and productivity than previously documented.

Admittedly, this paper speaks most directly to the effects of government aircraft purchases during the Second World War. The results suggest that high demand could spur productivity growth in other settings. However, there are some aspects of the war economy that may not translate neatly to a peacetime setting, e.g. workers' patriotism and price controls. Also, the aircraft industry may have been ripe for mass production on the eve of the war, making it particularly poised to "learn by necessity". I discuss concerns of external validity in Section 4.4 and Appendix D. While acknowledging these concerns, I note that it is also possible to overstate the uniqueness of the period. Aircraft firms were exempt from price caps; wages were frequently re-negotiated; and worker strikes and absenteeism were at historical highs, indicating that mundane motivations persisted alongside patriotism.

The remainder of the paper is organized as follows. Section 2 describes the data and the historical setting. Section 3 lays out the empirical strategy with the main results shown in Section 4. Section 5 gives a history and empirical evidence of the actions taken by plants to increase productivity. Section 6 concludes.

2 Data, Institutional Setting, and Historical Context

World War II brought the largest cyclical increase in public consumption in US history. Figure 1a shows government consumption as a share of GDP in the US from 1929 to today. The Second World War stands out as the single largest shock to government purchases. Government consumption and gross investment rose from 9% of GDP at the war's onset to 44% of GDP in 1945, declining again to 16% by 1948. The precise unemployment rate at the onset of World War II is debated, but it is generally agreed that the US economy was approaching full employment by the time the US officially entered the war in late 1941 (Figure 1b, Gordon & Krenn 2010).

The analysis that follows narrows in on aircraft production, which was the single largest procurement item in the military budget and became the largest industry during the war (War Production Board 1945 charts 3 and 11). Figure 1c shows that aircraft procurement peaked at 4% of GDP.

In May 1940, after the fall of France, President Roosevelt set an ambitious objective of producing 50,000 planes during the war (Fireside chat, May 26 1940). Economists Robert Nathan and Simon Kuznetz estimated that the US didn't have the productive capacity to meet this aim. Yet the US aircraft industry produced twice this number of aircraft in 1944 alone (War Production Board 1945 p. 10).

The aircraft industry was young: the average firm was founded in 1927 and the average plant in 1934. Table 1 gives summary statistics for the industry. In total, 38 firms operated 61 plants and produced 109 different aircraft models, with 141 plant-by-model combinations. For simplicity, I refer to plant-by-model combinations as "production lines," although some plants ran several production lines for the same model. The median firm was a single plant producing a single aircraft model. However, there was considerable variation: the 90$^{\text{th}}$ percentile firm operated three plants and the 90$^{\text{th}}$ percentile plant produced four models. Firm and plant sizes also varied significantly with the 75$^{\text{th}}$ percentile firm selling a total of $1.2 billion in aircraft, nearly 50 times more than the 25$^{\text{th}}$ percentile firm; and the 75$^{\text{th}}$ percentile plant employing 15,000 workers, almost 10 times the 25$^{\text{th}}$ percentile plant.

The industry was less concentrated than before or after the war: The Herfindahl-Hirschman Index of aircraft sales (by dollar value) declined slightly from 0.14 in 1939 to 0.10 in 1945, but rose again to 0.11 in 1947 (Reichardt, 1975). Douglass Aircraft, the leading firm, produced only 13% of all aircraft, by sales, a modest proportion by modern aircraft industry standards. There was just one acquisition (Vega by Lockhead) and one merger (Consolidated with Vultee) during the war, and only three small firms exited at the war's end. In contrast, the industry's post-war history has been one of consolidation and concentration: By the time of the Boeing-McDonnell Douglas merger in the late 90s, the industry's Herfindahl index was estimated at around 0.5 (Stock, 1999).

Procurement was under the purview of the Army Air Force and the Navy, in coordination with the War Production Board, which dictated the overarching war production strategy. Most contracts were Cost Plus Fixed Fee, covering suppliers' (audited) costs plus a pre-negotiated payment per aircraft delivered. Concerns over war profiteering led to a legal cap on markups (to 4% by the end of the war) and some contracts were renegotiated ex-post. As a consequence, most aircraft manufacturers' profit margins were lower than they were before or after the war (Smith 1991 pp. 248-293; Wilson 2018, chapter 4).

Aircraft firms, their subcontractors, and their suppliers were exempt from wartime price controls. While wages were were regulated and frozen at their March 1942 levels, they were frequently re-negotiated, leading to a 20% increase in the aircraft industry by 1945 (Smith 1991 pp. 399-403). Previously, most aircraft were made to order based on detailed specifications of the procuring agency, but this became untenable given the new production targets. The military therefore agreed to purchase standardized aircraft models, which were then modified in army or navy modification centers. Standardized aircraft aides productivity analysis, as it ensures consistent specifications across aircraft of the same model and mark.

Productivity data come from the Aeronautical Monthly Progress Reports, collected by the Army Air Force headquarters at Wright Field (later published in USAAF 1952). The military meticulously tracked war production, with all aircraft manufacturers submitting monthly reports. Productivity and production data from this source (Table 3) have been used in previous research, but previous researchers overlooked a second volume of reports, including detailed data on floor space, worker hours, and shift utilization (Tables 5 and 6).[1] To my knowledge, I am the first to have digitized these additional data. Reporting requirements and forms were the same for all plants and were extremely detailed. Figure A.1 in the appendix shows one of the standardized forms.[2]

Productivity measurement starts with the raw variable "Unit Man Hours: Entire Plane," which reports the worker-hours of the last plane delivered in the calendar month. This includes only manufacturing workers: overhead is reported separately. The measure includes hours worked in sub-assemblies, giving a consistent comparison when producers outsourced parts of the production.[3] The variable gives hours per aircraft at the product level, addressing the multi-product plant problem. There are benefits to measuring productivity at the aircraft level, but the last aircraft may be unrepresentative of the plant's average productivity. For comparison, I computed monthly labor productivity by dividing total aircraft deliveries by payroll hours for manufacturing workers, as is commonly done. The two measures are highly correlated but the comparison underscores the advantage of direct aircraft-level measurement. The aircraft-level data incorporates hours across all production months (USAAF 1952 p. 37): important, because production typically exceeded a calendar month (45 to 90 days in the case of Consolidated Vultee bombers, based on data from Consolidated Vultee archives, San Diego Air and Space Museum, Box 17). In contrast, dividing the number of aircraft by hours worked in the current month creates a mismatch between delivery

[1]Data reporting began in 1941, with 60% coverage prior before January 1943, 100% thereafter. However, this was the initial production date for most production lines.

[2]The military also gave plants a 150 page document with minute detail on how to uniformly report production, productivity, capacity utilization, and other data. (ATSC Regulation No. 15-36-3, Air Force Historical Research Agency, Maxwell Field, Reel A2050, starting on slide 850.) Consolidated Vultee Archives, San Diego Air and Space Museum, Box 34 documents how the second largest producer (by revenues) adopted these procedures internally.

[3]USAAF (1952) p. 37 states that these are "direct hours charged to a model... obtained from shop or worked orders and do not refer to payroll hours... They refer to hours expended on the airframe manufacturing process which includes machining, processing, fabricating, assembling, and installing all integral parts of the airframe structure, and rework prior to acceptance." Outsourced production hours are "the estimated direct man-hours it would require to perform within the facility that part of the airframe manufacturing process being produced outside the plant or plants of the reporting facility." The output per hour variable can then be seen as the number of hours worked to produce the portion of the aircraft that was produced in house. On one hand, this introduces some measurement error because the reporting plant is estimating the number of hours it would have taken to produce in-house the portion of production that was outsourced. On the other hand, this has the advantage that we no longer have to concern ourselves with differences in capital per worker between the main facility and feeder plants.

time and production time and severely misstates productivity at the beginning or end of a production batch. The running variable of monthly aircraft production is also from USAAF (1952), Table 3 with Civilian Production Administration (1947) Table 1, pp. 32-55, used to bring coverage from 60% to 100% prior to 1943.

The literature estimating production functions rarely observes plants' physical capital stock. Instead, the nominal (dollar value of the) capital stock is estimated by accumulating past (nominal) investment expenditure, or taken from accounting statements. In many cases, structures are largest component of capital expenditure and such nominal estimates of the capital stock confound differences in land prices and construction costs with real differences in the capital stock. In contrast, USAAF (1952), Table 5, gives a rare proxy for plants' physical capital stock: plant-level quarterly observations of the floor space actively used for manufacturing, measured in square-feet. This measure of physical capital is more comparable across plants and time. Further, the measure includes only floor area actively used for production and therefore incorporates capital utilization to some extent. It excludes office space and other non-production facilities.[4]

Plants also recorded all investments in plant and equipment exceeding $25,000, giving a measure of capital deepening.[5] Structures were the largest component (60%) of capital investment in the airframe industry during the war and we will see in Section 4 that investment in structures and equipment are both highly correlated with future physical floor space, indicating that capital expenditures only translate in to productive capital with a substantial lag.

Figure 2 shows time series indexes of aggregate aircraft production, hours worked, and floor space, from 1942 to 1945. It displays the number of aircraft (top panel) and total aircraft weight (bottom panel); the latter was used by by contemporary researchers to adjust for larger aircraft's greater production complexity. The figures give clear initial evidence of the great increase in productivity during the war. While hours worked and capital grew in tandem by a factor of close to 2.5 to 1944, aircraft production increased by a factor of 3.5, suggesting TFP growth of 35%, under a homogeneous of degree one production function. When measured in units of aircraft weight the growth is even more dramatic at approximately 250%.[6]

The data in USAAF (1952) (Table 6) also give a rare account of capital and labor utilization that hasn't been used in previous research. It includes details on the number of work shifts per day, the number of hours in each shift, and the number of monthly worker-hours active in each one of

[4]I interpolate quarterly floor space to monthly and allocate capital across production lines in the plant to equate the capital to labor ratio across all production lines within a plant in each month, as would optimally occur with standard constant returns to scale production functions. This assumes that the wage rate and rental rate of capital are the same across production lines, which is reasonable given that it was often the same workers shifting across production lines.

[5]"War Manufacturing Facilities Authorized by State and County,"War Production Board Program and Statistics Bureau, June 15, 1945. RG 179, box 984, NARA College Park

[6]This contrasts with Field's 2008; 2018; 2002 evaluation that TFP declined for the US economy as a whole in the war due to mis-allocation *across* industries. Be this as it may, Appendix Figure A.2 shows that productivity dispersion–often used to measure misallocation–across WWII plants declined over the course of the war, *within* the industry.

the shifts in each month. I use these to calculate shift utilization to capture capital utilization, as was done during the war and as suggested more recently by Basu *et al.* (2006). Scheduled working hours in the most active shift, always the Monday morning shift, are used to gauge production potential, with full capacity measured as the number of weekly work hours that would result if the plant operated 24×7 hours a week at this potential. Capital utilization is the ratio between *actual* monthly work hours and full capacity.[7] Additionally, I measure labor utilization as average weekly hours per worker, taken from the same table.[8]

Figure 3 shows the evolution of capital and labor utilization in the median airframe plant. Capital utilization was high and rising in the first year of direct US involvement in the war, peaking at 52%, nearly 90 hours a week. This is perhaps an unremarkable capital workweek by 21st century standards, but was well above typical pre- and post-war utilization rates of around 35% (60 hours per week). The year 1943 sees a surge in aggregate productivity (Figure 2), but a rapid *decline* in capital utilization for the remainder of the war. This suggests that the observed productivity surge was not merely high utilization masquerading as TFP. Instead, it appears that productivity growth substituted for high utilization rates, allowing plants to decrease utilization. The bottom panel of the figure reveals a similar trend in labor utilization, with the average production worker in the median plant working nearly 50 hours a week in 1942; this declines to roughly 45 hours a week by the end of the war.

3 Empirical Strategy

This section describes the paper's empirical strategy, beginning with a conceptual framework that motivates the estimation of "learning by necessity". I then compare this empirical strategy with the existing literature on learning by doing. Finally, I address the identification of demand shifts.

3.1 Conceptual Framework

This section outlines a simple theory of "learning by necessity": how high demand, relative to existing production capacity, induces productivity growth. It is used to frame the empirical analysis. For a more detailed treatment of a dynamic version of the model, refer to Appendix B.

[7] Wartime reports and the data suggest that the use of second shifts, night shifts, and Saturday shifts were the main source of variation in capacity utilization both over time and across plants.

[8] Shift utilization is imperfectly correlated with hours per worker (with a coefficient of 0.23). Shift utilization may seem like it measures labor utilization but it is better thought of a measure of capital utilization. For example, the Martin plant in Omaha had very high average weekly hours per worker (51.3) in early 1942, because many of its workers worked 7 days a week. However, it had very low capital utilization (37%) because the plant mostly worked 9-to-5, with very few workers in a limited evening shift and no night shift. In contrast, workers in the Douglas plant in Santa Monica worked 40 hours per week, but the plant had a high capital utilization (65%) rate because the plant spread its 15,000 workers nearly evenly over 3 shifts a day (operating 6 days a week).

Consider a plant p receiving orders to produce $Y_{mp,t}$ units of an aircraft model m in month t using capital $K_{mp,t}$. Capital is fixed so that $K_{mp,t} = K_{mp}$, but the plant can choose its rate of capital utilization $U_{mp,t}$: utilized capital in period t is $U_{mp,t}K_{mp}$. In the appendix, I extend the model to allow for costly capital adjustment, one period in advance. The empirical analysis incorporates labor as as a second factor of production and the appendix model shows that that the plant chooses to move the utilization of the two factors in tandem, so that no insights are lost in the single-factor model. When using a technology $z_{mp,t}$, the firm produces $F\left(U_{mp,t}K_{mp,t}|z_{mp,t}\right) = z_{mp,t}\left(U_{mp,t}K_{mp}\right)^{1-\alpha}$ units of the final good, with $0 < \alpha < 1$. Utilization incurs costs $\delta\left(U\right)$ per unit of capital, where $\delta\left(.\right)$ is increasing and convex and satisfies $\delta\left(0\right) = 0$. The utilization cost function represents maintenance and depreciation costs that increase with utilization.

In each period, the plant can operate a traditional technology z^T or upgrade to a modern technology $z^M > z^T$ at a monthly fixed cost A_{mp}. This cost could be a financial fixed cost, the cost of exerting managerial effort, or any other costly action that enhances productivity. I outline specific actions undertaken to enhance productivity in World War II aircraft production in Section 5 and Appendix E. Each firm draws the adoption cost from a uniform probability distribution $G\left(A_{mp}\right)$ with support $A_{mp} \in [0, \bar{A}]$. For simplicity, I also assume that technology is entirely reversible in each period, allowing for a static technology choice. It may seem peculiar that the firm cannot adjust factors of production but choose technology freely, but these assumptions are both relaxed in the dynamic model in the appendix. There, the firm makes a one-off and irreversible choice of technology but can adjust factors of production in each period at a cost. In the simple model presented here, fixed factors of production are necessary for meaningful factor utilization choices, and the flexible technology choice helps clarify the concept of "learning by necessity".

The plant chooses technology and utilization to minimize costs, period by period,

$$\min_{U_{mp,t}, z_{mp,t} \in \{z^T, z^M\}} \delta\left(U_{mp,t}\right) K_{mp} + A_{mp} \mathbb{1}\left(z_{mp,t} = z^M\right),$$

subject to satisfying demand,

$$z_{mp,t}\left(U_{mp,t}K_{mp}\right)^{1-\alpha} \geq Y_{mp,t}. \tag{1}$$

If plants receive a fixed payment per aircraft, cost minimization is equivalent to profit maximization. A cost-plus-fixed fee contract gives weaker incentives to minimize costs (see Section 4.4), but doesn't eliminate cost-savings incentives entirely, because future procurement contracts depend on plants' relative performance. For simplicity, I maintain the cost-minimization assumption, but note that incentives may be more subtle and complex, as evaluated in the literature on optimal procurement (McCall 1970, Laffont & Tirole 1988,Laffont & Tirole 1993, Bajari & Tadelis 2001; see Appendix D).

The problem boils down to a discrete choice of technology, whereby the firm chooses the modern technology if

$$C_{mp,t}=K_{mp}\delta\left(\frac{1}{K_{mp}}\left(\frac{Y_{mp,t}}{z^{T}}\right)^{\frac{1}{1-\alpha}}\right)-K_{mp}\delta\left(\frac{1}{K_{mp}}\left(\frac{Y_{mp,t}}{z^{M}}\right)^{\frac{1}{1-\alpha}}\right)\geq A_{mp},$$

where $C_{mp,t}$ are cost savings from choosing the modern technology. The two arguments of the $\delta\left(.\right)$ functions are the required utilization rates from (1) when choosing technologies z^T and z^M, respectively. Log-linearizing cost savings in month t around its value in period $t-1$ gives[9]

$$\Delta C_{mp,t}\cong K_{mp}U_{mp,t-1}\left[\delta'\left(U_{mp,t-1}\right)-\left(\frac{z^{T}}{z^{M}}\right)^{\frac{1}{1-\alpha}}\delta'\left(U_{mp,t-1}\left(\frac{z^{T}}{z^{M}}\right)^{\frac{1}{1-\alpha}}\right)\right]\Delta\log Y_{mp,t}. \tag{2}$$

The term in brackets is positive if $\delta''(.)>0$, therefore cost savings are increasing in demand. Intuitively, high demand increases the marginal cost of utilization and more so on the steeper end of the cost curve, where the plant finds itself if it uses the traditional technology. The plant adopts the modern technology if $C_{mp,t}>A_{mp}$, which occurs with frequency $G\left(C_{mp,t}\right)$. Therefore,

$$E\log z_{mp,t}=G\left(C_{mp,t}\right)\log z^{M}+\left(1-G\left(C_{mp,t}\right)\right)\log z^{T}. \tag{3}$$

A Log-linearized version of this equation implies

$$E\Delta\log z_{mp,t}\cong\frac{1}{\bar{A}}\log\left(\frac{z^{M}}{z^{T}}\right)\Delta C_{mp,t}. \tag{4}$$

Combining (2) with (4) gives

$$E\Delta\log z_{mp,t}\cong\Upsilon\left(U_{mp,t-1}\right)\Delta\log Y_{mp,t}, \tag{5}$$

where

$$\Upsilon\left(U_{mp,t-1}\right)\equiv\frac{K_{mp}U_{mp,t-1}}{\bar{A}}\log\left(\frac{z^{M}}{z^{T}}\right)\left[\delta'\left(U_{mp,t-1}\right)-\left(\frac{z^{T}}{z^{M}}\right)^{\frac{1}{1-\alpha}}\delta'\left(U_{mp,t-1}\left(\frac{z^{T}}{z^{M}}\right)^{\frac{1}{1-\alpha}}\right)\right].$$

A Taylor expansion of $\Upsilon\left(U_{mp,t-1}\right)$ around its value at the median plant, $\bar{U}_{t-1}$, is:

$$\Upsilon\left(U_{mp,t-1}\right)\cong\Upsilon\left(\bar{U}_{t-1}\right)+\Upsilon'\left(\bar{U}_{t-1}\right)\left[U_{mp,t-1}-\bar{U}_{t-1}\right].$$

I show in Appendix C that $\Upsilon\left(\bar{U}_{t-1}\right)>0$ always, and that $\Upsilon'\left(\bar{U}_{t-1}\right)>0$ if (but not only if) $\delta'''(.)\geq$

[9]The two-dimensional linearization strategy used here draws on Boehm & Pandalai-Nayar (2022).

0.[10] Combining this last equation with (5) motivates an estimating equation of the form

$$\Delta \log z_{mp,t} = \beta_1 \Delta \log \left(Y_{mp,t}\right) + \beta_2 \left[U_{mp,t-1} - \bar{U}_{t-1}\right] \Delta \log \left(Y_{mp,t}\right),$$

where $\beta_1 = \Upsilon\left(\bar{U}_{t-1}\right)$ and $\beta_2 = \Upsilon'\left(\bar{U}_{t-1}\right)$.

For the practical task of estimation, I modify this equation in a few ways. First, I include fixed effects and lags of the explanatory variable. I discuss their importance for causal inference below. Second, with lags of the dependent variable, we can use the level of $\log Y_{mp,t}$ rather than its first difference, which is useful because the instrument, discussed shortly, is more predictive of the monthly level of demand than its month-on-month growth. Third, we measure utilization $U_{p,t-1} - \bar{U}_{t-1}$ at the plant level at the war's onset, rather than with a single lag, because utilization early in the war is less likely to be endogenous to current productivity growth. Fourth, we transform the continuous variable $U_{p,0}$ into a binary dummy variable that takes on the value of 1 if the plant was above the sample median of capital utilization. This eases interpretation of the coefficient, which becomes a comparison between plants that had high and low capital utilization. The robustness exercises in the following section include a regression with the continuous value of utilization. Finally, the specification is dynamic and allows for lags between the demand shock and the time of technology adoption, for gradual technology adoption, or for gradual effects of technology adoption on TFP. This is done through a local projections specification as follows:

$$\Delta_h \log z_{mp,t+h} = \alpha_{mp} + \alpha_t + \beta_h^{LBD} \log Y_{mp,t} + \beta_h^{LBN} \mathbb{1}\left(U_{p,0} > \bar{U}_0\right) \log Y_{mp,t} + \text{controls} + \varepsilon_{mp,t}^h, \quad (6)$$

where α_t and α_{mp} are month and production line (plant-by-model) fixed effects. The operator Δ_h gives the growth rate of a variable from month $t-1$ to $t+h$, so that $\Delta_h \log z_{mp,t+h} \equiv \log z_{mp,t+h} - \log z_{mp,t-1}$. The variable $\mathbb{1}\left(U_{mp,0} > \bar{U}_0\right)$ equals 1 for plants with above-median utilization at the beginning of the war and zero otherwise. All specifications include six lags of the the independent variable $Y_{mp,t}$ and some include additional controls. The direct effect of initial capacity utilization $U_{p,0}$ or $\mathbb{1}\left(U_{p,0} > \bar{U}_0\right)$ is omitted as it is absorbed by production line fixed effects α_{mp}.

There are two coefficients of interest. First, β_h^{LBD} is the traditional "learning by doing" coefficient. It measures productivity growth in a plant following a 1% increase in demand in period t. (6) is dynamic and controls for lags of the explanatory variable. Controlling for lags gives a nearly perfect correlation between current production used here and "experience", the explanatory variable in previous studies.

Second, β_h^{LBN} is the "learning by necessity" coefficient. It quantifies the differential impact of

[10]This condition holds for a quadratic cost function, for example. It also holds for cost functions that ensure that utilization is bounded, e.g. costs go to infinity as we approach full utilization. Further, the condition $\delta'''(.)$ is sufficient, but not necessary.

demand on productivity in high-utilization plants compared to those with lower utilization. In contrast, the traditional learning literature imposes $\beta_h^{LBN} = 0$.

The raw archival data report labor productivity, which I convert to TFP using a more general production function than the one outlined above:

$$Y_{mp,t} = F\left(U_{mp,t}K_{mp,t}, H_{mp,t}L_{mp,t}|z_{mp,t}\right) = z_{mp,t}\left[\left(U_{mp,t}K_{mp,t}\right)^{1-\alpha}\left(H_{mp,t}L_{mp,t}\right)^{\alpha}\right]^{\gamma},$$

where $L_{mp,t}$ is the number of production workers and $H_{mp,t}$ is hours per worker. The parameter γ allows for economies of scale, with $\gamma > 1$ representing increasing, $\gamma < 1$ decreasing, and $\gamma = 1$ constant returns to scale. With $y_{mp,t} \equiv \frac{Y_{mp,t}}{H_{mp,t}L_{mp,t}}$ denoting labor productivity, we can write:

$$\Delta_h \log z_{mp,t+h} = \Delta_h \log y_{mp,t+h} - (1-\alpha)\left(\Delta_h \log k_{mp,t+h} + \Delta_h \log U_{mp,t+h}\right) - (\gamma - 1)\Delta_h \log S_{mp,t+h}, \tag{7}$$

where $k_{mp,t} \equiv \frac{U_{mp,t}K_{mp,t}}{H_{mp,t}L_{mp,t}}$ is (utilized) capital per hour worked and $S_{mp,t} \equiv \left(U_{mp,t}K_{mp,t}\right)^{1-\alpha}\left(H_{mp,t}L_{mp,t}\right)^{\alpha}$ is production scale.[11]

3.2 Conventional Learning by Doing Estimates

The post-war learning-by-doing literature reports correlations between cumulative output and output per worker as reflecting a "learning curve". But these correlations aren't necessarily informative of demand's causal impact, because demand, experience, and productivity are all jointly determined. Reverse causation isn't merely a theoretical possibility: It is also very likely. Further, in the parlance of modern econometrics, estimated learning curves suffer from substantial pre-trends. This is illustrated in Figure 4, which shows regression coefficients in a standard learning-by-doing regression with pre- and post-trends. (Log) labor productivity (aircraft per hour) are regressed on experience (log cumulative production) and month and production line fixed effects. The existing literature reports the coefficient at $h = 0$. Horizons $h < 0$ show the correlation between current experience and *past* productivity. The regressions show strong pre-trends meaning that production lines accumulating more experience were already more productive in the preceding twelve months. Higher cumulative production at time zero is likely the result of previously high productivity. Horizons $h > 0$ show the correlation between current experience and future productivity. If anything, productivity *declines* in the months after a plant gains experience.

Mishina (1999) (pp. 148, 153) speaks to the challenges of estimating learning curves. He notes that cumulative output follows an upward trend by definition, so that any trend decline in unit

[11] I include factor utilization in "production scale," following Basu & Fernald (1997) and Basu *et al.* (2006) Results are robust to defining $F\left(U_{mp,t}K_{mp,t}, H_{mp,t}L_{mp,t}|z_{mp,t}\right) = z_{mp,t}\left(U_{mp,t}K^{\gamma}_{mp,t}\right)^{1-\alpha}\left(H_{mp,t}L^{\gamma}_{mp,t}\right)^{\alpha}$, which allows economies of scale for both utilized and unutilized capacity.

costs, or trend increase in productivity, will be attributed to "learning". This issue may even be present when using cumulative instruments, e.g. macro variables accumulated over time, as in Benkard (2000). Modern time series econometric methods, which control for lags of the running variable, are a step towards addressing this problem. However, even with two way fixed effects and lags of the running variable, it is plausible that the military diverted demand to production lines with high (anticipated) productivity. I therefore propose a an instrument for aircraft demand.

3.3 Identification Strategy

I instrument the monthly output of each production line with the aggregate output of all other production lines producing the same broad aircraft type in that month. This approach draws on historical evidence that demand for broad aircraft types (e.g. bombers vs. fighter planes) was determined by strategic considerations, not relative productivity in their manufacture. This contrasts with demand for specific aircraft models within a broad category (e.g. B-24 vs. B-17 bombers) or across plants (Douglas vs. Boeing), where demand may well have been affected by plants' relative (expected) productive capacity. I divide aircraft into six broad types: bombers, communications, fighters, trainers, transport, and other specialized aircraft. The instrument $I_{mp,t}$ for demand $Y_{mp,t}$ of aircraft model m in plant p in month t is given by $I_{mp,t} = \sum_{\pi \neq p} \sum_{\mu \in \mathbb{M}_m} Y_{\mu\pi,t}$, where $\mathbb{M}_m$ is the set of aircraft models of the broad type that includes model m.

Instrument relevance requires a correlation between production lines of the same broad aircraft type. Relevance is borne out in F statistics reported in the figures of the following section. The exclusion restriction requires that the national demand for a broad aircraft type affects the subsequent productivity growth in the production line in question only through the correlated demand directed to that production line.

The source of variation captured by the instrument is illustrated in Figure 5, which shows the number of total aircraft delivered for four aircraft types. The four faced different demand fluctuations, with known historical interpretations. Early war production was for lend-lease assistance to US allies in Europe. This primarily took the form of fighter aircraft (e.g. for the Battle of Britain), leading to a boom in fighter production in 1940-1941. Fighters were also used as escorts for US merchant ships during this period. US direct involvement in the war began in December 1941. US military strategy following Pearl Harbor anticipated a heavy reliance on aerial bombing, causing an inflection in bomber aircraft in 1942 and a surge in demand the following year.[12]

Demand for transport aircraft took off only later, supporting the island-hopping operations in

[12] The President's program of January 1942 required that "Offensive planes [be] stressed, and the war department immediately asked that the previous goal of 1,000 heavy bombers a month be increased to 2,000 at the earliest possible date," US Civilian Production Administration (1947b), chapter 46, p. 74.

the Pacific and the invasion of Italy in 1943.[13] Demand for fighter aircraft rose again in mid-1943, when it became apparent that both bomber and transport aircraft benefited from fighter escorts.[14] Trainer aircraft were naturally needed in greater quantities in the early war years than later.

A threat to identification arises if these relative demand shifts were due to differential expected productivity growth across broad aircraft types. But the historical literature indicates that strategic considerations were paramount in determining procurement schedules for broad categories of munitions. In September 1943, a report by the War Manpower Commission[15] notes that (p. 2)

> The primary purpose of the periodical overhauling of aircraft schedules is to shift emphasis from one model to another in the light of combat experience and military needs.

War Production Board (1945) p. 11 explains:

> In 1944, our war production had to meet front-line needs, constantly changing with the shifting locales of warfare, the weaknesses and strengths demonstrated in combat, and our inventiveness as well as the enemy's. Less emphasis was placed on increasing quantities of everything required to equip an army, a navy, and an air force, and more on those specific items needed to replace battle losses and to equip particular forces for particular operations.

The same document (p. 13) narrows in on aircraft production:

> The complex causation of program changes is illustrated by the aircraft program. Each quarterly aircraft schedule represented a cut under its predecessor. In part this reflected lower than anticipated combat losses... [In 1944, t]he demand for four-engine long-range heavy bombers, transport vessels and heavy artillery ammunition rose dramatically during the year, while the need for training planes, patrol vessels, mine craft, and radio equipment fell off in varying degrees.

In summary, procurement of broad categories of aircraft was driven by strategic needs, not aircraft plants' expected productivity. Of course, procurement agencies carefully monitored plant-level productivity and purchased aircraft within these broad categories from plants they viewed as most able to deliver. But this source of variation is discarded, rather than captured by, the

[13]See Air Force Historical Research Agency, Reel 1009, p. 1608 "Airborne Missions in the Mediterranean" on the use of C-47 transport aircraft for glider and paratrooper landings in operations Husky, Landbroke, and Fustan in Sicily. On transport aircraft in the North Burma campaign, see Taylor, Joe G., 1957, Air Supply in the Burma Campaign, USAF Historical Studies No. 75, USAF Historical Division, Maxwell Airforce Base, reel K1009.

[14]Major Lesher, Lee A. (1988). "The Evolution of the Long-Range Escort Doctrine in World War II" United States Air Command and Staff College. An important inflection point was a failed strategic bombing mission on Schweinfurt, Germany in August 1943, that exposed the need for fighter escorts in bombing campaigns.

[15]War Manpower Commission, "Manpower Problems in the Airframe Industry" Sep 18, 1943, RG221, 111, Box 1 National Archives College Park.

instrument. Further, technological improvements and new varieties of aircraft may have moved demand across aircraft models within broad categories (from "heavy" B-17 to "very heavy" B-29 bombers, for example), but not across the broad categories we consider (B-17 bombers to P-39 fighter aircraft), as they were hardly good substitutes in military operations.

4 Learning by Doing and Learning by Necessity

This section summarizes the main results. We begin by restricting $\beta_h^{LBN} = 0$ in (6) to consider the average response of productivity to demand, as in traditional learning-by-doing regressions. We then turn to an unrestricted version of (6), which allows an interaction between demand and capacity utilization: *learning by necessity*.

Impulse responses are based on two-stage least squares. The second stage is estimated using local projections (Jordà 2005), as in (6). In the first stage, (log) aircraft demand and its interaction with initial capacity utilization are instrumented with the (log of the) leave-one-out instrument $I_{mp,t}$ and its interaction with the utilization variable.

4.1 Learning by Doing

The learning-by-doing local-projections impulse responses are shown in Figure 6. These are estimates of (6), imposing $\beta^{LBN} = 0$. Panel 6a gives the response of labor productivity: aircraft per hours worked. Shaded areas in this and subsequent figures give 90% and 95% confidence bands.[16] Regressions include time and plant-by-model fixed effects and are in growth rates relative to productivity at time $t-1$. Hence they reflect the relative cumulative growth in labor productivity at each horizon in a production line receiving 1% higher demand, as predicted by the instrument described in the previous section. The specification controls for six lags of the explanatory variable (log aircraft produced), and dummy variables equaling one if the production line produced more than 25% or 50% of total aircraft of its broad type (e.g. bombers) in that month.[17] Labor productivity increases by around 0.4% per each percent increase in demand, within the first 12 months. Estimates become very noisy beyond the reported horizon.[18]

[16] The instrument is strong, by standard criteria, with an F-statistic of 25 in the 12-month horizon regression. We can reject a bias due to weak instruments greater than 10% according to a Montiel Olea & Pflueger's (2013) test. F-statistics for subsequent regressions are reported in the figure notes. An Anderson-Rubin test gives a p-statistic < 0.01 at the 12-month horizon in this and all subsequent LBD and LBN regressions.

[17] Plants that are dominant in a specific month are non-compilers in the first stage, because production in less significant remaining plants isn't very predictive of output in these dominant ones. These are uncommon occurrences: The monthly median observation produces 4% of its broad type of aircraft that month, and the 90[th] percentile observation produces 25%.

[18] Figure A.3 in the appendix shows the OLS version of the baseline IV regression. OLS estimates could be biased upwards or downwards, particularly when looking at the response to demand "shocks", i.e. controlling for past production. On one hand, the War Production Board may have directed demand to plants it expected to deliver aircraft

The production drive was associated with facility expansions; we control for this by calculating TFP as the residual from a constant-returns-to-scale Cobb-Douglass production function with a capital share of 20%, as in (7) with $\alpha = 0.80$ and $\gamma = 1$. The capital share was chosen to match the average ratio of capital costs to the sum of capital and labor costs in aircraft plants during the war.[19] All results are robust to using a capital share of $\frac{1}{3}$, as is common in the macro literature, or to simply controlling for the capital to labor ratio, as we will shortly see. Figure 6b shows a TFP response of similar magnitude to that of labor productivity.

Figure A.4 in the appendix shows the pre-trends of labor productivity and TFP before the shock to demand. There are signs of a slight pre-trend in labor productivity in the run up to the shock, but this is eliminated when considering TFP.

Figure 6c shows the response of production to the 1% increase in demand. The initial shock to aircraft demand leads to a persistent surge in production. The responses in Figure 6 should therefore be considered the response of labor productivity and TFP to an increase in demand with a half-life of slightly over a year.

Capital $K_{mp,t}$ measures *active* floor space. This already accounts to some extent for capital utilization, but TFP in Figure 6b also adjusts for capital utilization $U_{mp,t}$, measured as outlined in Section 2. The impulse response reflects an increase in TFP above and beyond cyclical increases in productivity arising from higher rates of utilization as in Basu *et al.* (2006). Figure A.5 in the appendix shows similar results without accounting for capital utilization.

Although structures reflected more than 60% aircraft plants' capital stock during the war, structures alone don't produce airplanes and Thompson (2001) has shown that capital deepening explains a large portion of shipyards' productivity growth during the war. Fortunately, the War Production Board recorded every investment in plant expansion exceeding $25,000 in this period, whether publicly or privately financed, and these investments are separated into "structure" and "equipment".[20] TFP's response to a demand shock is nearly identical when controlling for each plant's cumulative investment in equipment, as I report in Table A1 in the appendix. This is because investment in equipment is highly correlated with investment in structures (see Figure A.6

at higher productivity, which would lead to an upward bias in OLS estimates. However, it is clear from histories of the war production effort that the War Production Board was more concerned about a plant's ability to deliver a large quantity of aircraft than plants' cost/productivity. This objective, together with the War Manpower Commission's goal of directing demand to lower-pressure labor markets, may have in fact shifted demand to lower productivity plants, leading to a downward bias in OLS.

[19] Source: Aircraft firm balance sheets from Mergent Archives, for the sample of available firms (Curtiss, McDonnell, Nash, Northrop, and Republic). Labour costs are the sum of payroll and benefits. The cost of capital was calculated as depreciation plus the value of property, plant, and equipment times the interest rate. The government offered aircraft plants funding at 4% and this is taken as the interest rate, but doubling or tripling this interest rate to account for a risk premium changes the calculation very little, because depreciation was an order of magnitude larger. Hall (1990) and Basu & Fernald (1997) show that calibrating production function coefficients in this way is robust in the presence of markups.

[20] War Production Board, *War Manufacturing Facilities Authorized by State and County*, RG179, 221.1, Box 986, NARA, College Park.

in the appendix).[21]

Labor productivity and TFP are measured in physical units (TFPQ) so that responses reflect an increase in aircraft produced rather than changes in prices or markups. Model fixed effects reflect narrowly defined models, which controls for (major) product quality changes. Plant-by-model fixed effects also control for any (persistent) quality differences across plants producing the same model. Given the enormous increase in the size and quality of aircraft over the war, estimates shown here are likely lower bounds to quality-adjusted demand-induced productivity growth.[22]

Recent research has warned of potential bias in two-way fixed effects regressions, particularly if treatment effects are heterogeneous. An estimator of de Chaisemartin & D'Haultfoeuille (2020) corrects for this bias, but requires a set of groups whose treatment status remains constant throughout the sample. Instead, I apply a modified version of Goodman-Bacon's (2021) recommendation to compare production lines that were treated early with those that were never treated. When interacting the instrument with a dummy variable equalling one in first half of the sample, results are unchanged (albeit with a weaker instrument, see Figure A.7 in the appendix).

It is difficult to compare the results reported here to the existing literature for two reasons. First, the impulse responses shown here are dynamic, in contrast to the static responses shown in Thompson (2001), for example. Second, to allow a causal interpretation, responses here are to a *shock* to demand, rather than cumulative experience, as in the existing literature. Nevertheless, the 12-month response are of similar magnitude to the impact responses reported in Benkard (2000) and Thompson (2001), and to the naïve contemporaneous learning elasticity reported in Figure 4.

4.2 Learning by Necessity

Turning to learning by necessity, I estimate an unrestricted version of (6). Aircraft demand $Y_{mp,t}$ and its interaction with an indicator variable measuring whether a plant initially had high capital utilization are jointly instrumented by the "leave one out" instrument and its interaction with the indicator variable. Figure 7 plots the local projections impulse responses: the estimated β_h^{LBN} coefficients. This represents the response of productivity to a one percent increase in demand in plants with initially high capital utilization relative to those with lower utilization. High-pressure plants show larger increases in both labor productivity (top panel) and TFP (bottom panel). The magnitudes are substantial with both labor productivity and TFP growing by $\beta_{12}^{LBN} = 0.28$ percentage points more in plants that were initially more constrained at a 12-month horizon. This is on top of

[21] Figure A.6 in the appendix also illustrates the importance of a physical measure of capital. Capital investments in structures correlate with floor space only with a 9-month lag, after controlling for 2-way fixed effects, so investment data may give incorrect measures of TFP, particularly at high frequency.

[22] Results might overstate productivity growth if demand pressures caused plants to cut corners and produce lower quality aircraft. However, I show in Appendix D that there are few indications of systemic demand-induced quality problems.

the $\beta_{12}^{LBD} = 0.23$ percent productivity growth seen in plants with lower utilization (Table A2 in the appendix), themselves operating at utilization rates well above the pre- and post-war norms.

Demand shocks are identified through the instrument, but capital utilization isn't randomly assigned. Plant by model fixed effects absorb productivity differences in plants with differing initial rates of capacity utilization. The remaining concern is that the interaction between capacity utilization and demand shocks is endogenous. Put simply, the concern is that learning by doing is stronger in high utilization plants because of a confounding factor that happens to be correlated with initial capacity utilization. Capacity utilization is endogenous, of course, and was indeed an important consideration in procurement decisions (Fairchild & Grossman 1959 chapter VI). It is reassuring that initially high- and low-utilization plants were similar on most dimensions (Table A3 in the appendix). However, one correlate does stand out: high utilization plants were older on average. This is because older plants were known entities at the onset of the war and they were the first to receive contracts before they'd had a chance to expand their capacity. However, FigureA.8 in the appendix shows that results are, if anything, stronger when controlling for plant age and its interaction with aircraft demand.

Investigating high pressure on labor, as opposed to capital, I use three metrics to evaluate labor shortages. The first is labor utilization, measured at the plant level as average hours per worker in a plant. The second is the wage rate in the plant's labor market excluding plants in the aviation industry, used to capture local labor market tightness. The third is the War Manpower Commission's classification of the tightest labor markets.[23] Table A4 in the appendix shows that these various metrics of capital and labor shortages are correlated but the correlations aren't perfect. Figure A.9 in the appendix shows similar learning by necessity estimates when considering labor rather than capital utilization.

4.3 Robustness

So far we have assumed that production exhibits constant returns to scale, with $\gamma = 1$ in (7). Increasing returns may certainly have played a role, although our data excludes overhead labor and floor space: the fixed costs that are a major source of increasing returns. Nonetheless, two diagnostics indicate that the rise in productivity goes beyond scale effects. Figures 8a and 8b repeat the learning by doing and learning by necessity regressions, but now with controls for the growth of each factor of production from horizon $t-1$ to $t+h$. The regression controls for the growth in (logs of) the capital to labor ratio, hours worked, floor space, and the capital utilization

[23]The War Manpower Commission classified each labor market in the US into four categories in each quarter, with 1 representing the tightest labor markets and 4 representing markets with labor surpluses (unemployment). Nearly half of the production lines in this study were in counties of the first category and an additional 30% were in the second. The dummy in question takes on a value of one of the plant was in a county classified in the first category.

ratio, as in (7). Results are similar to the baseline specification, shown in a dashed line in the figure. Controlling for each factor separately allows for greater flexibility in functional forms, but results are similar when controlling for a single variable measuring scale $S_{mp,t}$ as in (7) and defined in Section 3.1. The estimated coefficient on scale in this case indicates slightly increasing returns to scale, with a value that fluctuates around $\gamma = 1.1$, consistent with Basu *et al.* (2006).

Figures 8c and 8d take a different tack. I run multiple regressions, where the outcome variable TFP is a residual from the production function, using (7). In each regression, I impose a different value of γ, the parameter governing returns to scale. For a wide range of assumed returns-to-scale, we see productivity growth beyond what is explained by economies of scale. In fact, the estimated response of TFP to demand shocks increases the greater are the assumed economies of scale. This is because factors of production themselves *decline* following the demand shock, increasing the required growth in TFP needed to explain explain the increased production, if there are greater scale economies. (The responses of factors of production can be seen in Figure A.10 in the Appendix.) It is perhaps puzzling that plants decreased production inputs in face of high demand, but recall that all responses are relative to other plants. Responses merely suggest that plants receiving demand shocks expanded capacity at no greater pace than other plants (themselves scaling up as part of the nationwide wartime expansion).

Aircraft demand was persistent and productivity may have responded to cumulative, not only current, changes in demand, especially at longer horizons. Figure 9 addresses this issue in two ways. First, I estimate a multiplier-type impulse response, estimating a modified version of (6):

$$\Delta_h \log z_{mp,t+h} = \alpha_{mp} + \alpha_t + \beta_h^{LBD} \log\left(\sum_{\tau=t}^{t+h} Y_{mp,\tau}\right) + \beta_h^{LBN} \mathbb{1}\left(U_{p,0} > \bar{U}_0\right) \log\left(\sum_{\tau=t}^{t+h} Y_{mp,\tau}\right) + \text{controls} + \varepsilon_{mp,t}^h.$$

The coefficient β^{LBD} now gives the change in productivity from time $t-1$ to $t+h$ resulting from a 1% increase in *cumulative* production over the same period. The results in the figure are from a two-stage-least squares regression, where the (log of) $I_{mp,t}$ now instruments for (log) cumulative production $\left(\sum_{\tau=t}^{t+h} Y_{mp,\tau}\right)$.[24] Similarly, β_h^{LBN} estimates how much larger this response is for plants with initially high capacity utilization. Figures 9a and 9b show multipliers of similar magnitudes to the previous specifications, because demand for aircraft in "treated" plants remained consistently 1% higher for the first 12 months than in the "control" group, with the gap narrowing afterwards. The log-log specification can be interpreted as the percent increase in productivity per one percent increase in accumulated experience, as in traditional learning-curve estimates.

[24] I follow Ramey & Zubairy (2018) and use the instrument at time t rather than the cumulative instrument. The cumulative production of broad aircraft types over longer horizons is more likely to be endogenous to productivity in plants producing those broad types than at higher frequency.

Figures 9c and 9d take a different approach: a difference-in-differences local projections regression proposed by Dube *et al.* (2023). This includes leads of the explanatory variable, in addition to lags, in a regression of the form:

$$\Delta_h \log z_{mp,t+h} = \alpha_{mp} + \alpha_t + \beta_h^{LBD} \log Y_{mp,t} + \beta_h^{LBN} \mathbb{1}\left(U_{p,0} > \bar{U}_0\right) \log Y_{mp,t} + \sum_{\ell=t-L,\ell\neq t}^{t+h} \gamma_\ell \log Y_{mp,\ell} + \text{controls} + \varepsilon_{mp,t}^h.$$

This specification includes separate controls for aircraft production in each period between the demand shock and the estimated productivity response. According to Dube *et al.* (2023), responses can now be interpreted as productivity growth following a 1% shock to demand, holding constant any future increases in demand following the initial shock. The figures show that results are attenuated but similar to the baseline specification.

Productivity spillovers across plants are plausible and these could bias estimates of the response of demand to productivity. I use the the national demand for a broad aircraft type (excluding the plant in question) as an instrument for demand for the aircraft in a particular plant. With productivity spillovers, the plant in question might benefit not only from demand directed to that plant, but also from demand-induced productivity in other plants of that same broad type. This could lead to an over-estimate of the effects of demand on productivity. The concern can be assuaged by controlling for the mediating factor of (average) productivity growth from month $t-1$ to $t+h$ in peer production lines. Given the instrument used, the most relevant peer group is other production lines producing the same broad aircraft types. Figure A.11 in the appendix shows that results are barely affected by this control. The figure also reports regressions that control for the average productivity growth in other production lines that relied on the same motor manufacturer, or the production volume therein. These control for potential productivity spillovers through supply chains, with little change in results. Importantly, these results in no way reject the possibility that there were productivity spillovers across plants. They merely suggest that spillovers were not induced by the identified demand shocks.

Additional robustness exercises are shown in Tables A1 and A2. Beyond the robustness checks already reported, we can see robust results when controlling for cumulative production; cumulative investment in equipment; weighting observations by the production line's cumulative wartime production to date, using a continuous measure of initial capital utilization; or a time varying measure of (lagged) capital utilization.

4.4 External Validity

Is learning by necessity a peculiarity of the Second World War production drive? Appendix D discusses the historical context and its external validity. Wartime price and wage controls suppressed inflationary pressures that might emerge in a peacetime setting. However, the aircraft industry was exempt from price controls and airplane prices *declined* dramatically, making a prize freeze unnecessary. Cost-plus-fixed-fee contracts provide weaker cost-cutting incentives than do fixed-fee contracts that are the default in modern procurement (McCall 1970, Bajari & Tadelis 2001; see Appendix D). With a fixed-fee contract, cost savings contribute to contractor profits, but these are passed through to the buyer under cost-plus-fixed-fee. The industry later faced caps on profit margins, further eroding incentives to cut costs. Now cost savings reduced profits, which were a fixed percentage of costs. However, firms still had an incentive to contain costs to expand quantity produced and to secure future procurement contracts.

Separately, government-induced demand may be different from other demand surges. Firms with market power may have weak incentives to reduce costs when facing high market demand because increased production partly cannibalizes existing profits. In contrast, the government, a monopsonistic buyer of military materiel, has greater power to dictate quantities produced and negotiate contracts that incentivize productivity growth.

Wage controls were frequently renegotiated and wages increased by 20% in aircraft-producing counties during the war. Table A4 in the appendix shows that wages were correlated with reported labor shortages, indicating that the price mechanism was still at play, at least to some extent.

Standardized products are arguably a necessary precondition for mass production. All plants in our dataset delivered standardized aircraft, but differed in the extent to which they adopted mass production techniques. Standardized production was new to this industry, but was commonplace throughout the 20$^{\text{th}}$ century, as in the pre- and post-war automobile industry, the post-war aircraft industry, and "just in time" manufacturing later in the century. Standardization was certainly catalyzed by the large wartime demand surge. However, the aircraft industry may have been at a developmental stage that made it poised for this transition and had the distant cousin of the automotive industry to learn from. It is difficult to assess whether the findings reported here are applicable to industries that are already applying production techniques on the knowledge frontier, are already producing standardized products, or have not yet matured to the point of standardization.

Although the wartime aviation industry may have been poised for a transition to mass production, there is no indication that learning curves were steeper in this setting. Estimates presented in this study are comparable those found in the peacetime aircraft industry (Benkard, 2000), wartime liberty ship building (Thompson, 2001), and truck manufacturing (Lafond *et al.*, 2022), although these all show static rather than dynamic estimates and employ different identifying strategies. These studies don't investigate "learning by necessity" and it is difficult to infer whether this phenomenon depends on the industry's developmental stage.

I was unable to locate data on aircraft faults, but the historical narrative gives little to suggest that there were systemic quality problems in airframe production or that aircraft manufacturers "cut corners" to achieve production targets. Military modification centers, serving as the final checkpoint for aircraft before deployment, were tasked to inspect and repair any faults in aircraft plants' deliveries. If manufacturers traded productivity for quality, these centers would have experienced increased workloads. However, as demonstrated in the appendix (Table A5), there was no correlation between modification center employment and productivity, suggesting that higher productivity didn't come at the expense of quality.

Patriotism may have motivated workers during the war and it is hard to evaluate whether "learning by necessity" requires levels of worker motivation above those typically seen in peacetime. It is difficult to adjudicate this question in our setting, but it is also easy to understate the extent to which more mundane considerations persisted in wartime. Wartime histories summarized in Appendix D show that worker absence, turnover, and strikes–all potentially inimical to productivity growth–were at historical highs around the time aircraft production peaked.

With these caveats in mind, we now inspect some concrete actions taken by airframe manufactures to investigate mechanisms through which productivity increased.

5 Mechanisms: What Plants Did to Increase Productivity

How, then, do capacity-constrained plants increase production in face of surging demand? A voluminous historical literature has studied the productivity "miracle" of the wartime production drive. Here, I focus here on three explanations widely acknowledged in wartime and historical analyses (War Production Board 1945, US Civilian Production Administration 1947a, Nelson 1950, Janeway 1951, Jones & Angly 1951, Herman 2012, Klein 2013). I focus on active decisions, more aligned with the concept of learning by necessity, than on passive learning. Appendix E gives more detailed historical case studies of these practices.

The first significant change was the move from "job shop" production methods to "line" production methods. Craven & Cate (1955) write that the "most conspicuous improvement [in the aircraft industry] was the switch from handwork methods to those of mass production" (p. 385). Mass production methods, long established in the automotive industry, were met with skepticism in the aircraft industry. Klein (2013) p. 71 claims that at the beginning of the war, "Nobody had yet found a way to bring mass-production techniques to airplane building, and prospects for doing so did not look promising". Nonetheless, the enormous demand pressures of the war induced technological adoption.

To evaluate this claim empirically, we assembled a new data set based on newspaper searches for terms related to production technique upgrades. Search terms included the the aircraft firm's name (with plant location verified in the body of the article) and terms indicating modern production technology (MASS and PRODUCTION appearing within 5 words from each other; ASSEMBLY and LINE within 5 words; PRODUCTION and LINE within 5 words; AUTOMOTIVE). A research assistant read each relevant article and a count variable was incremented by one at the earliest mention of a new production technique. For example, an October 1941 Business Week article identified through this procedure states that "The Glenn L. Martin Co. factories in Baltimore, MD have set up a mass-production technique new to aircraft manufacture — a belt-conveyor line... The line has already cut man-hours on these subassemblies in half... to speed bomber production." The "Mass Production" count variable is then increased by one for the Martin Baltimore plant in October 1941.

Sources included the digital archives of main national (business) publications (New York Times, Wall Street Journal, Business Week, Fortune). Local newspapers were searched through the archival platforms Chronicling America and Newspapers.com. Additionally, annual reports for aircraft companies were accessed via Mergent Archives.

By our count, nearly half the aircraft plants adopted new production techniques, with the average plant adopting three new methods (Figure A.12a in the appendix). The higher frequency methods used for the analysis of demand and productivity are less suited to analyze the evolution of methods, which changed at low frequency. Nevertheless, Figure 10 provides indicative evidence linking technology adoption to the volume of production and capacity constraints. It gives a scatter plot of the cumulative number of new production methods adopted in plant p up to month t against the cumulative production of aircraft model m in plant p up to month $t - 12$ (one year earlier). The scatter plot is residualized from time, plant, and aircraft model fixed effects. Notably, there is a statistically significant association between cumulative production ("learning" or "experience") and the subsequent adoption of mass-production methods, but only for plants with high capital utilization.

Outsourcing was a second factor discussed in contemporary reports and indeed the share of outsourced work grew from 10% to 40% of employment over course of the war (Figure A.12b in the appendix). Aircraft plants of the 1930s assembled the entire aircraft in house. However, with the introduction of mass production techniques featuring interchangeable parts produced at narrow tolerances, it became feasible to farm out parts of the production process to feeder plants. Formalizing this argument, Figure 11a shows how the share of outsourced production responded to increased demand in an estimation of (6), with outsourcing as the dependent variable. Plants with high utilization rates outsourced 20 percentage points of their workforce more than low utilization plants, in response to a 1% demand shock. The magnitude is notable considering that the average outsourcing rate was 30%. The effect appears cyclical and transient. Further, while outsourcing was used to increase production volumes, it isn't obvious that it increases productivity. The latter requires the subcontractor to be sufficiently productive and free the "mother plant" to produce the remaining components more efficiently.

Many studies claim that improved labor relations–the third factor I investigate–played a crucial role in driving labor productivity. Labor motivation problems are well documented. The median plant lost 7% of it workforce to absenteeism and 6% to quits in late 1943 (Figure A.12 in the appendix, based on new archival data on labor conditions in plants[25]). Demand pressures appear to affect labor: In the half year following a 1% demand shock, plants with low labor utilization saw a 7 percentage point increase in absenteeism. However, Figure 11b shows that absenteeism increased by *less* in high hour-per-worker plants. It estimates (6), with the absence rate as the outcome variable and mean hours per worker over the course of the war as the utilization measure. This counter-intuitive finding–that labor problems increased less in high pressured plants–may suggest that management actions, taken in plants under under duress, were enough to offset these pressures. Appendix E documents specific measures taken by management to improve labor relations when faced with high demand and labor dis-satisfaction.

6 Conclusion

A traditional view of the transmission of government spending posits that increased demand boosts leads firms to soak up under-utilized employment or capital. The neoclassical view focuses increased labor supply. Both theories suggest that cyclical demand does little to expand output at high rates of utilization, nor can they affect productivity. This was also the common view at the onset of the Second World War, where economists warned that the economy could not sustain the planned war production drive, while the military insisted that it must. Using new archival data from this period, we see that plants with rates of capacity utilization met the production challenge through productivity gains. They did so not merely through passive learning, but through active investments in new production methods, improving working conditions, and experimenting with different supply chain management techniques.

The evidence in this paper is based on archival data on airframe production during the Second World War. It is possible that wage and price controls dampened inflationary pressures that might emerge in other settings, but aircraft prices *declined* dramatically during the war, indicating that productivity gains were more than sufficient to counteract inflationary pressures due to high demand. Demand pressures no doubt lead to inflation, but this study suggests a silver lining:

[25]Bureau of Labor Statistics, "Labor Statistics for the Aeronautical Industry," Reel 2237, PDF pp. 2210-2284; and Army Air Force Material Command, "Aircraft Program Progress Report," several volumes, Reel 2237, PDF pp. 2285-2648; both from the archives of the Air Force Historical Research Agency, Maxwell Air Force Base, AL.

Businesses may find ways to enhance productivity when facing exceptional demand. Of course, the findings are based on a particular industry and historical episode, and further research could beneficially examine other periods and industries at different developmental stages.

The case for restrained anti-trust policy in face of learning dynamics (Dasgupta & Stiglitz 1988, Benkard 2000) would appear even stronger with learning by necessity, with its non-linear relationship between demand and productivity. However, the war episode also demonstrates a lesser trade-off between efficiency and market concentration than often presumed. Smaller producers, not only market leaders, gained from robust demand conditions, which appear to have delayed the inevitable march towards market consolidation in this industry.

World wars will hopefully remain a rarity, but there may be lessons from wartime for the age of Covid-19 and wars in Eastern Europe and elsewhere. During the pandemic, some sectors showed substantial excess capacity and shortages were seen in others. Geopolitical risks and sanctions put additional supply constraints on firms worldwide. While such constraints have no doubt contributed to recent inflation, the findings in this paper suggest that private sector firms can at times find ingenious ways to overcome them.

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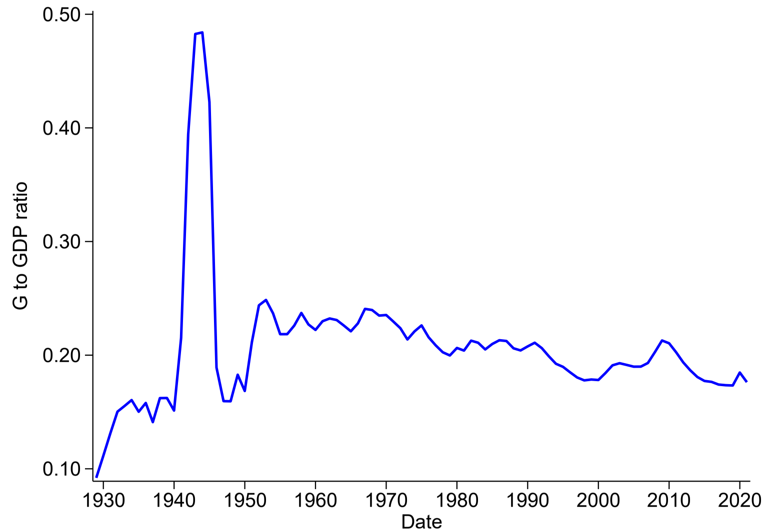
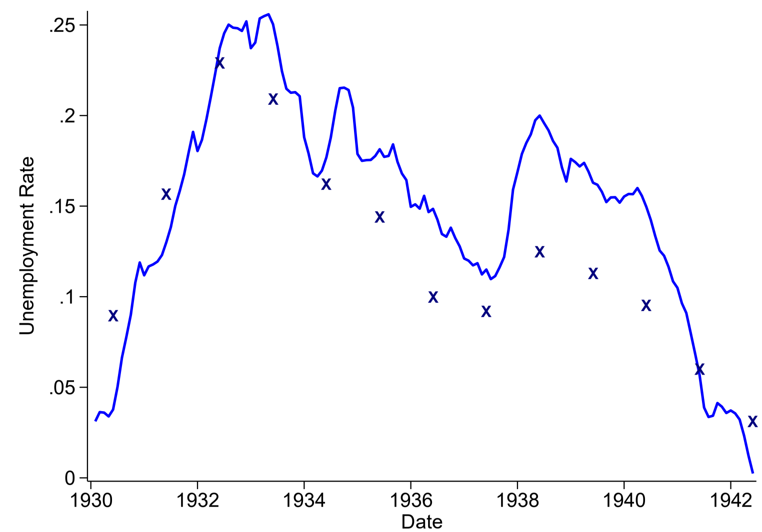
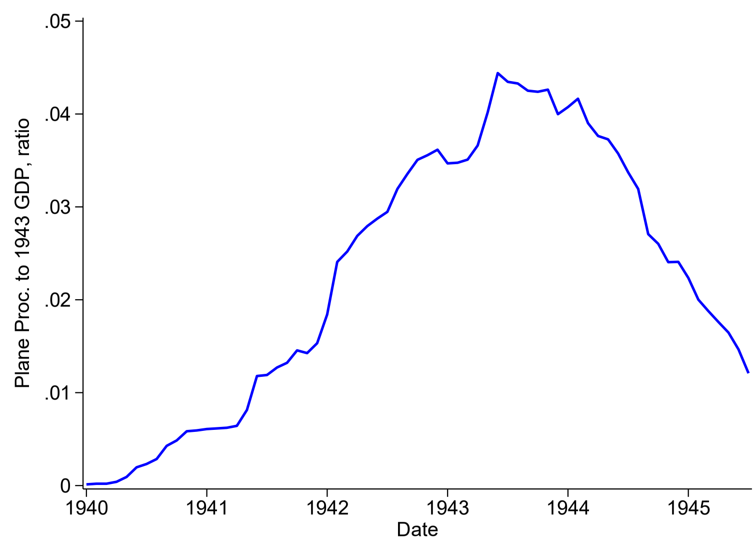
Figure 1: Government Spending, Unemployment, and Aircraft Procurement in the Second World War



(a) Public consumption and gross investment, share of GDP



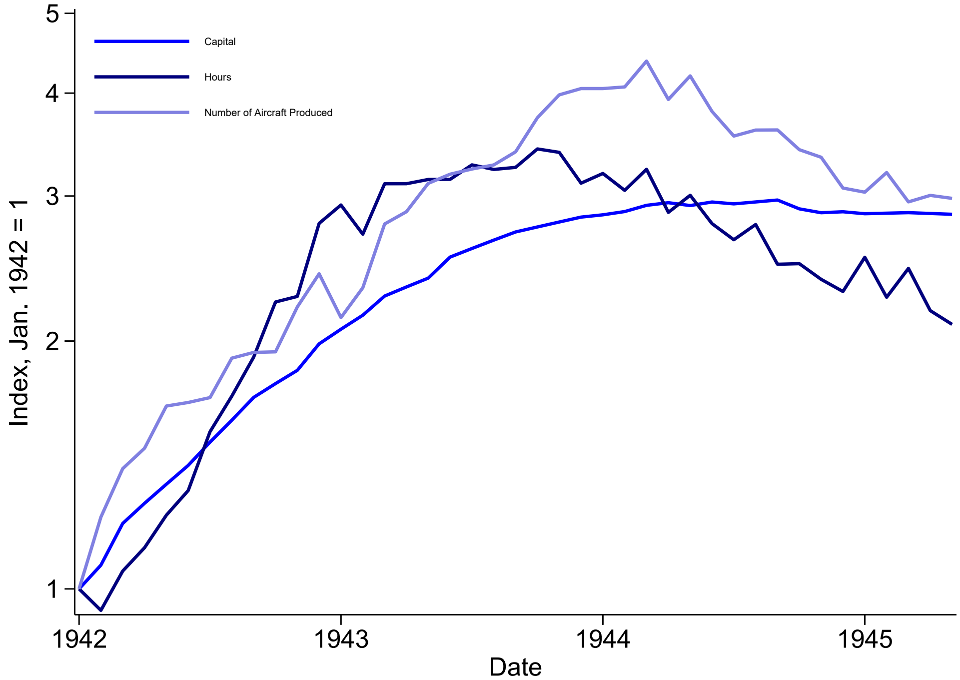
(b) Unemployment



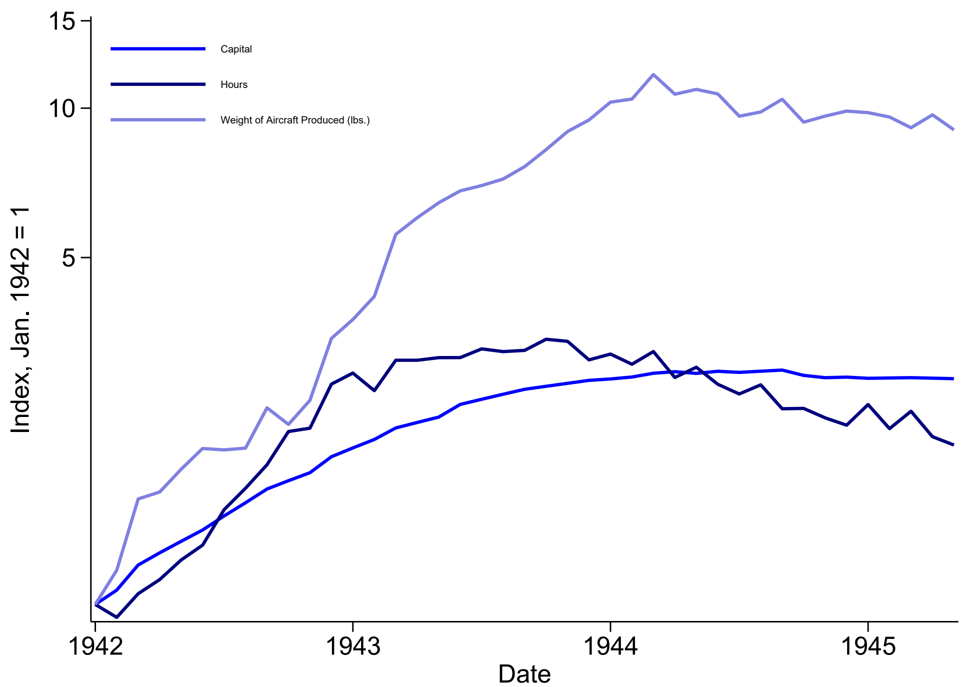
(c) Aircraft Procurement, share of 1943 GDP

Note: Panel (a) shows government consumption expenditure and gross investment as a share of GDP in the US since 1929. Source: Bureau of Economic Analysis, Fed FRED series GDPA and GCEA, retrieved from FRED, Federal Reserve Bank of St. Louis. Panel (b) shows the US unemployment rate from the great depression to the US's formal entry into the Second World War. Monthly series in line: National Bureau of Economic Research, Unemployment Rate for United States [M0892AUSM156SNBR], retrieved from FRED, Federal Reserve Bank of St. Louis. Annual series in Xs: Table Ba470-477 in *Historical Statistics of the United States*, Carter (2006). The latter is considered more authoritative but is available only at annual frequency. Panel (c) shows annualized government aircraft procurement as a share of 1943 GDP. Source: Civilian Production Administration (1945), Bureau of Economic Analysis, Fed FRED series GDPA, and the author.

Figure 2: Capital, Labor, and Output for the US Aircraft Industry in World War II



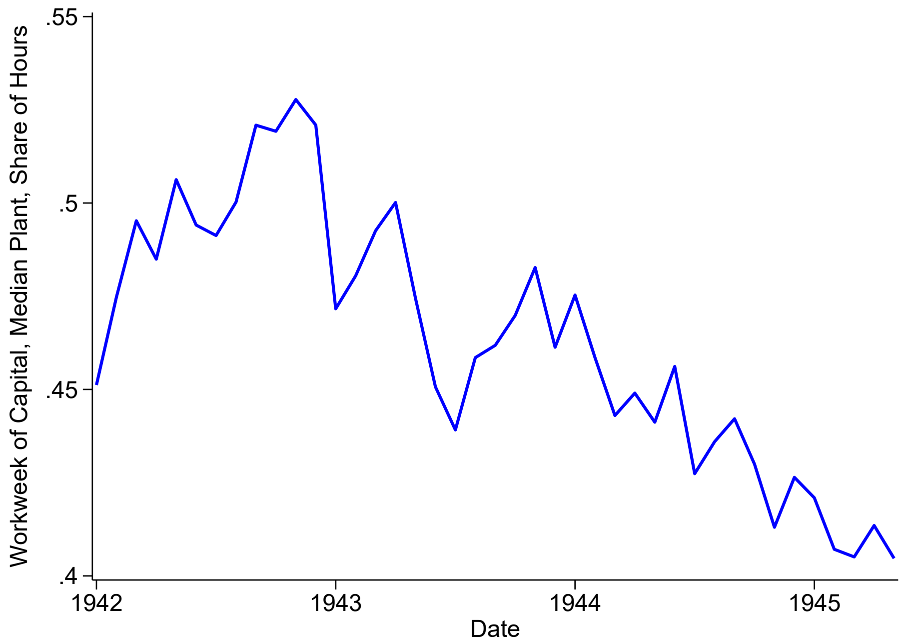
(a) Capital, Labor, and Number of Aircraft Produced, Indexes



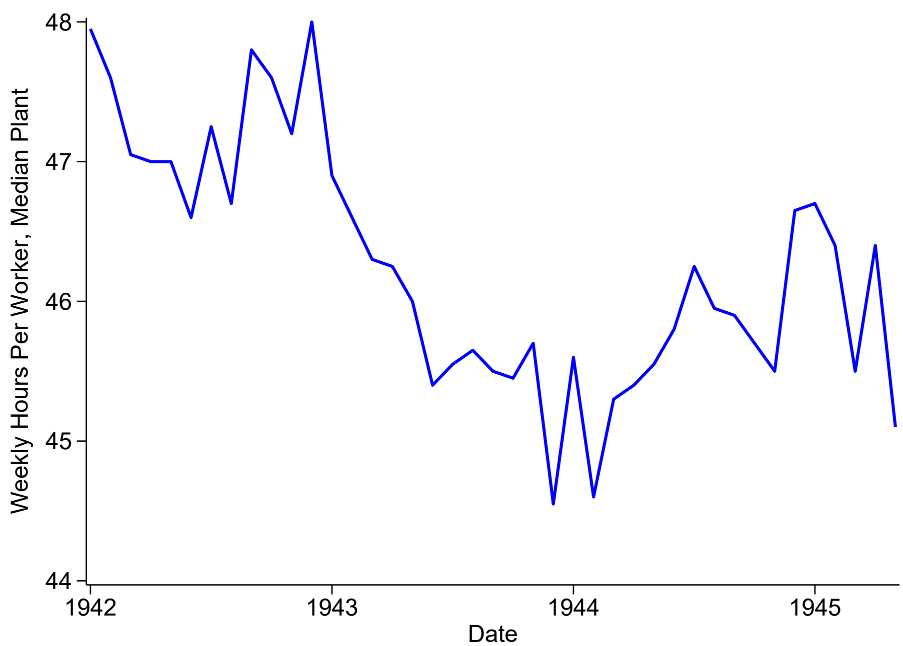
(b) Capital, Labor, and Weight of Aircraft Produced, Indexes

Note: The figures show aggregate inputs to and outputs of production in the airframe industry during World War II. Capital is the aggregate quantity of physical capital used in production, proxied by active floor space in airframe plants. Hours are aggregate hours of workers in direct aircraft manufacturing. Panel (a) measures output as number of aircraft. Panel (b) measures output as aggregate aircraft weight. Values of all variables are normalized to 1 in January 1942. Source: USAAF (1952) Vol. 1 Tables 2 and 3, Vol 2. Table 5, Civilian Production Administration (1947), Table 1, "Airplanes by Plant," pp. 32-55 and the author.

Figure 3: Capital and Labor Utilization in Airframe Plants



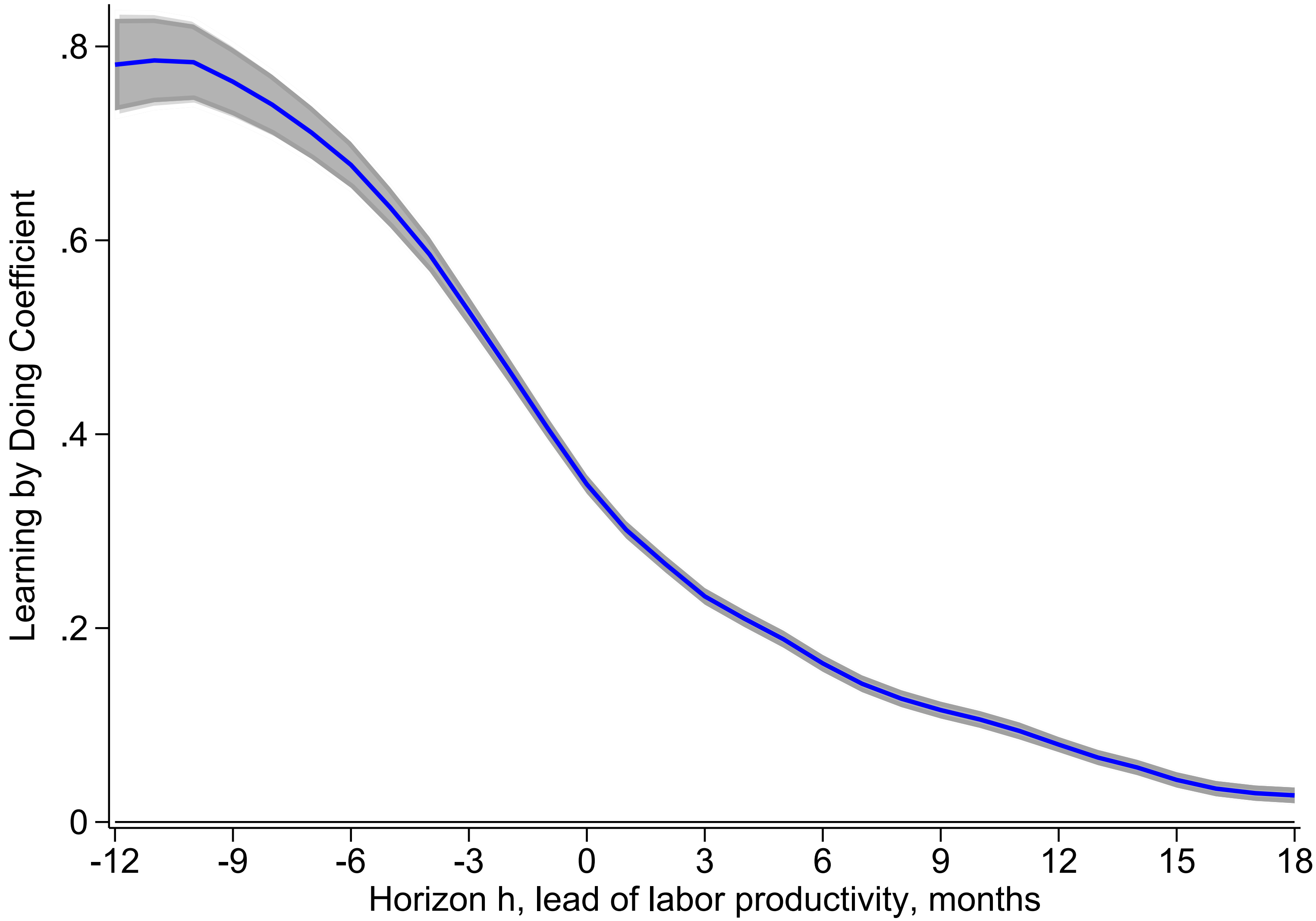
(a) Capital (Shift) Utilization



(b) Hours per Worker

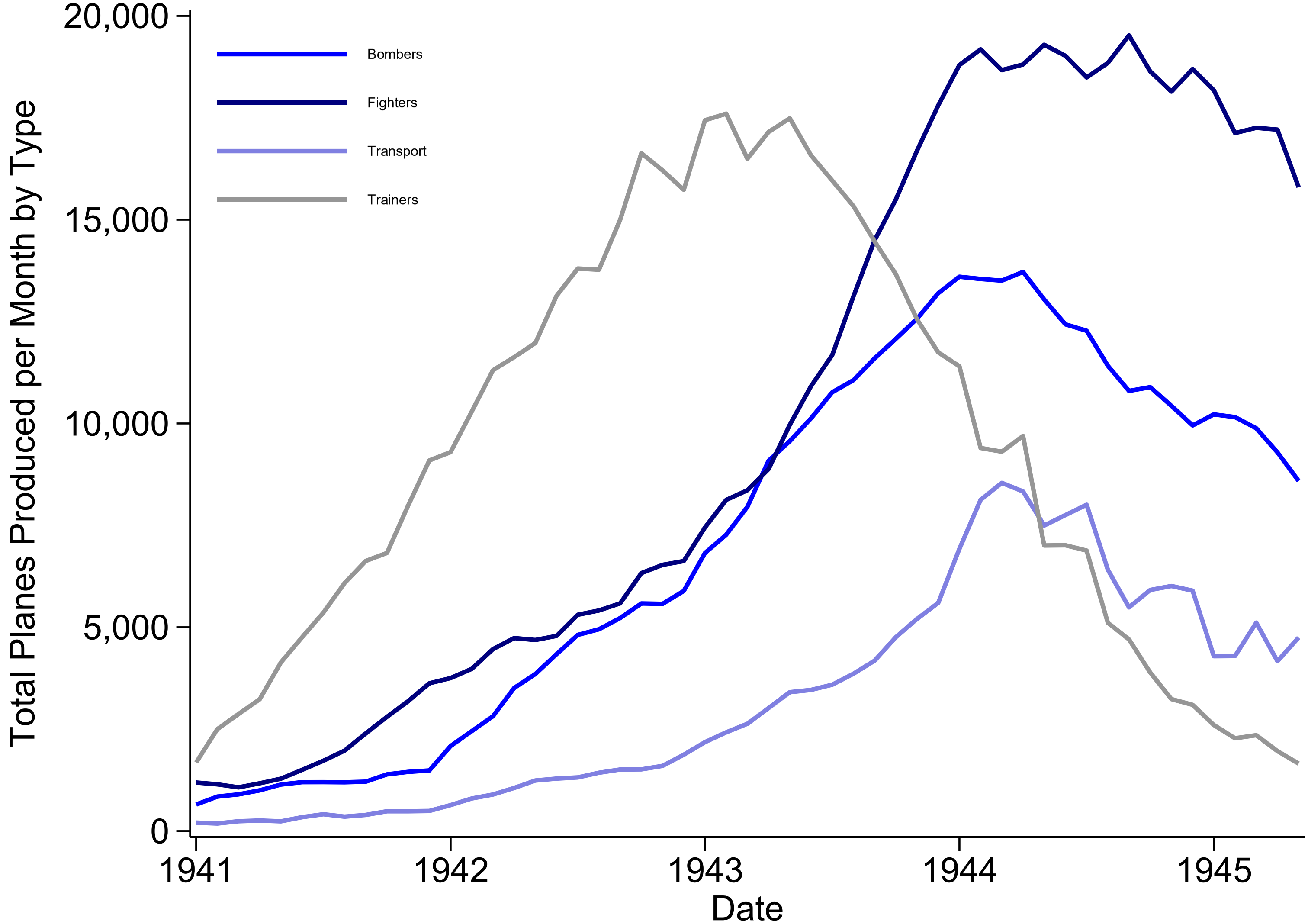
Note: Panel (a) shows shift utilization for the median airframe plant, estimated as described in Section 2, measured as share of hours out of 24×7. Panel (b) shows hours per worker in the median airframe plant. Source: USAAF (1952) Vol. 2, Table 6 and the author.

Figure 4: Dynamic Response and Pre-Trend of Labor Productivity in a Traditional Learning By Doing Regression



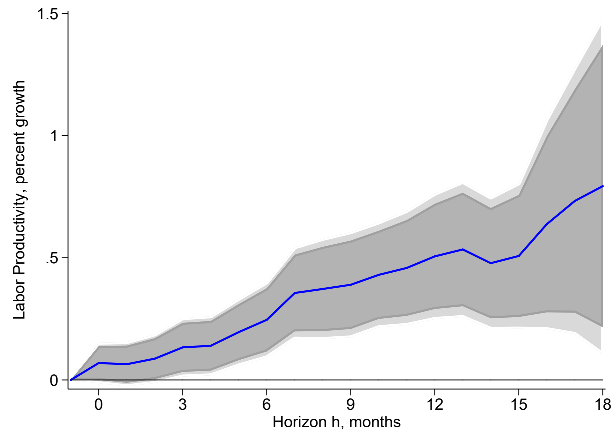
Note: The figure shows the OLS regression coefficient of (log) aircraft per hours worked at month $t+h$ per (log) cumulative aircraft produced at time $t=0$, with the x-axis giving the horizon h, in months. Shaded areas show 95% Newey-West confidence intervals. Traditional LBD regressions report the coefficient of $h=0$, showing a correlation between labor productivity and cumulative production. However, the responses show a substantial pre-trend, strongly indicating that production accumulated due to previous high productivity.

Figure 5: Total Aircraft Production by Broad Aircraft Type

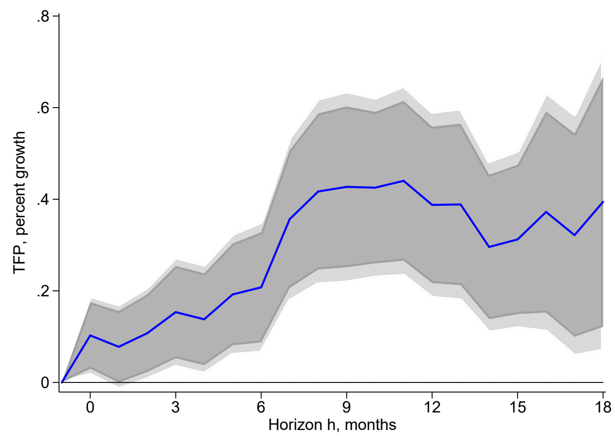


Note: The figure illustrates the instrument described in Section 3. It shows total monthly aircraft production of fighters, bombers, transport aircraft, and trainers. Differential demand for the aircraft types was driven by different strategic needs as the war progressed. The identifying assumption is that different production trajectories across plant types was driven by this differential demand, not other productivity drivers. Fighter aircraft were more prominent in lend-lease acquisitions by US allies in 1941, leading to a boom and bust in their production in 1941-42. Bombers were more central to the US war strategy and saw an inflection point after Pearl Harbor and again in 1943. Transport aircraft become increasingly important later in the war to supply troops when the US had "boots on the ground" in Europe and the Pacific. Trainers were obviously more important earlier in the war. Fighter aircraft saw a resurgence mid-war with increasing realization that bomber and transport aircraft benefited from having fighters as escorts. See historical narrative in Section 3. Source: USAAF (1952) Vol. 1 Table 3, Civilian Production Administration (1947) "Airplanes by Plant," pp. 32-55, and the author.

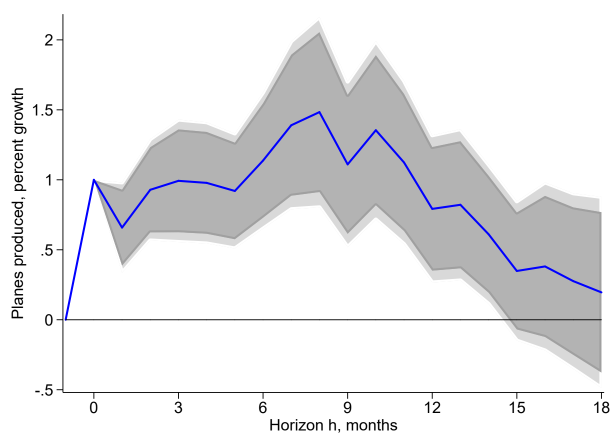
Figure 6: Responses to a 1% Shock to Aircraft Demand



(a) log Aircraft per Hour Worked



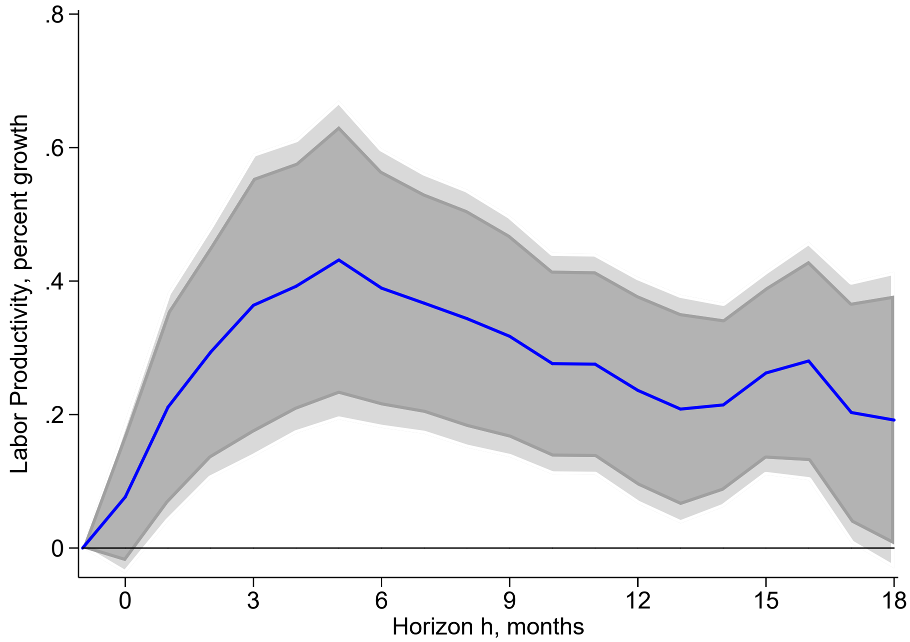
(b) TFP (capital utilization adjusted)



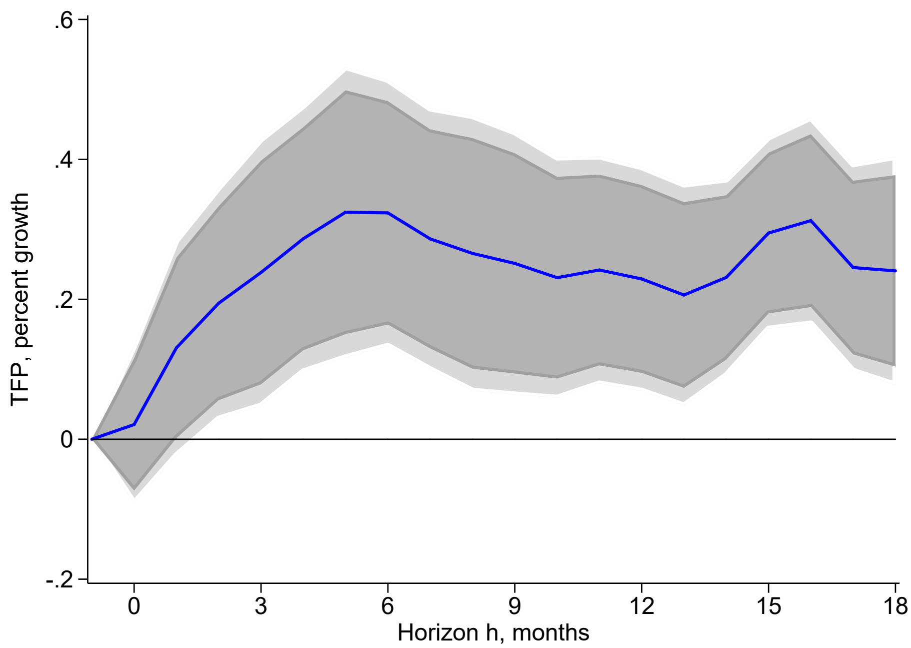
(c) log Aircraft Produced

Note: The figure shows the response of (a) log aircraft per hour worked, (b) TFP (adjusted for capital utilization), and (c) production, to a one percent shock to aircraft demand. Responses are the β_h^{LBD} coefficients of local projections estimates of (6), with $\beta_h^{LBN} = 0$ imposed. Aircraft demand is predicted by the instrument described in Section 3. Shaded areas show 95% Newey-West confidence intervals. First stage F-statistic at 12-month horizon = 24, 30, and 25 in the three panels.

Figure 7: Response of Output per Hour Worked and TFP to a 1% Shock to Aircraft Demand in High Capital Utilization Plants (relative to Low)



(a) Output per Hour Worked

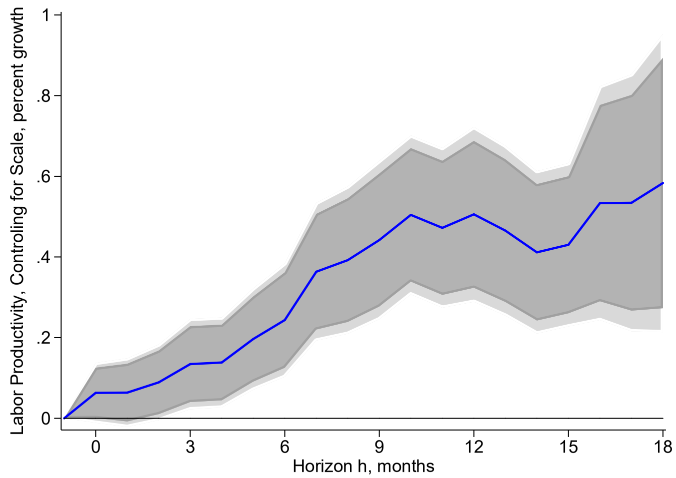


(b) TFP

Note: The figure shows responses of (a) log aircraft per hour worked and (b) TFP (adjusted for capital utilization) to a one percent shock to aircraft demand in plants with above median initial capital utilization relative to those with below median utilization. Responses are the β_h^{LBN} coefficients of local projections estimates of (6). Aircraft demand and its interaction with initial capacity utilization are jointly predicted by the instrument described in Section 3 and its interaction with initial capacity utilization. Shaded areas show 90% and 95% Newey-West confidence intervals. First stage F-statistic at 12-month horizon = 14 and 15 in the top and bottom panels, respectively.

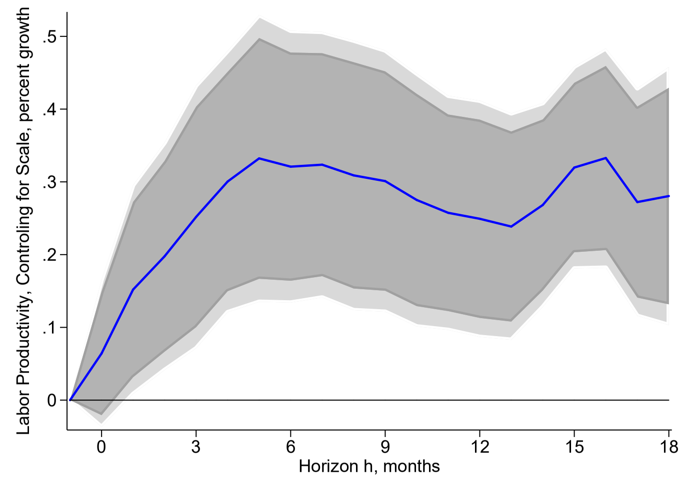
Figure 8: TFP or Economies of Scale?

Labor Productivity Response

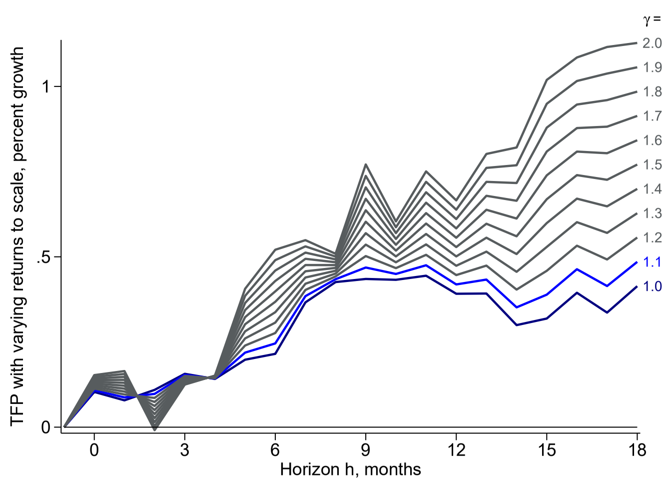


(a) Controlling for Growth of Factors of Production

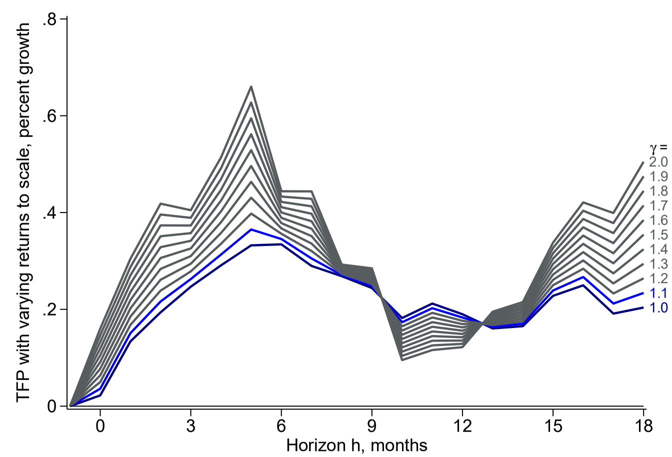
Labor Productivity Response: High vs. Low Capital Util.



(b) Controlling for Growth of Factors of Production



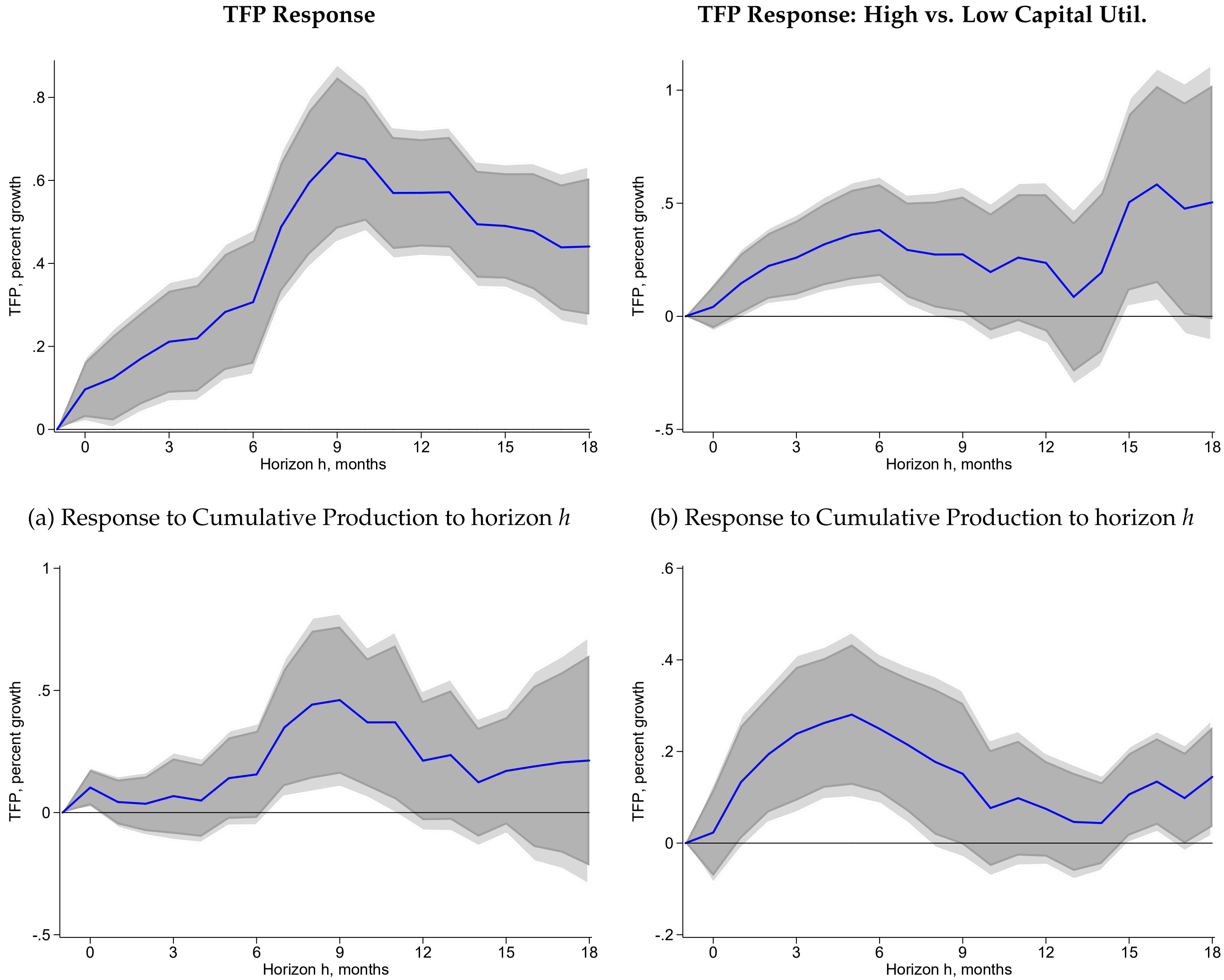
(c) Residualizing with a Range of Scale Parameters



(d) Residualizing with a Range of Scale Parameters

Note: The figure shows the response of productivity to a one percent shock to aircraft demand: local projections estimates of (6). Panels on the left-hand side show responses in the average plant: the β_h^{LBD} coefficients when $\beta_h^{LBN} = 0$ is imposed in (6). Panels on the right-hand side show responses in plants with above median initial capital utilization relative to those with below median utilization: β_h^{LBN} in an unrestricted version of (6). Aircraft demand and its interaction with initial capacity utilization are jointly predicted by the instrument described in Section 3, and its interaction with initial capacity utilization. In the top-row panels, the dependent variable is labor productivity and the regressions control for the growth (log-difference) in hours worked, productive floor space (proxying for capital), and capital utilization from month $t-1$ to month $t+h$, at each horizon h. The bottom row shows responses of TFP as measured by (7): labor productivity residualized for the scale of production. Each line in the bottom-row panels reflects a different value of the scale parameter γ. Shaded areas show 90% and 95% Newey-West confidence intervals. First stage F-statistic at 12-month horizon = 30 and 17 in panels (a) and (b), respectively.

Figure 9: Correcting for Induced Production and Demand



(a) Response to Cumulative Production to horizon h

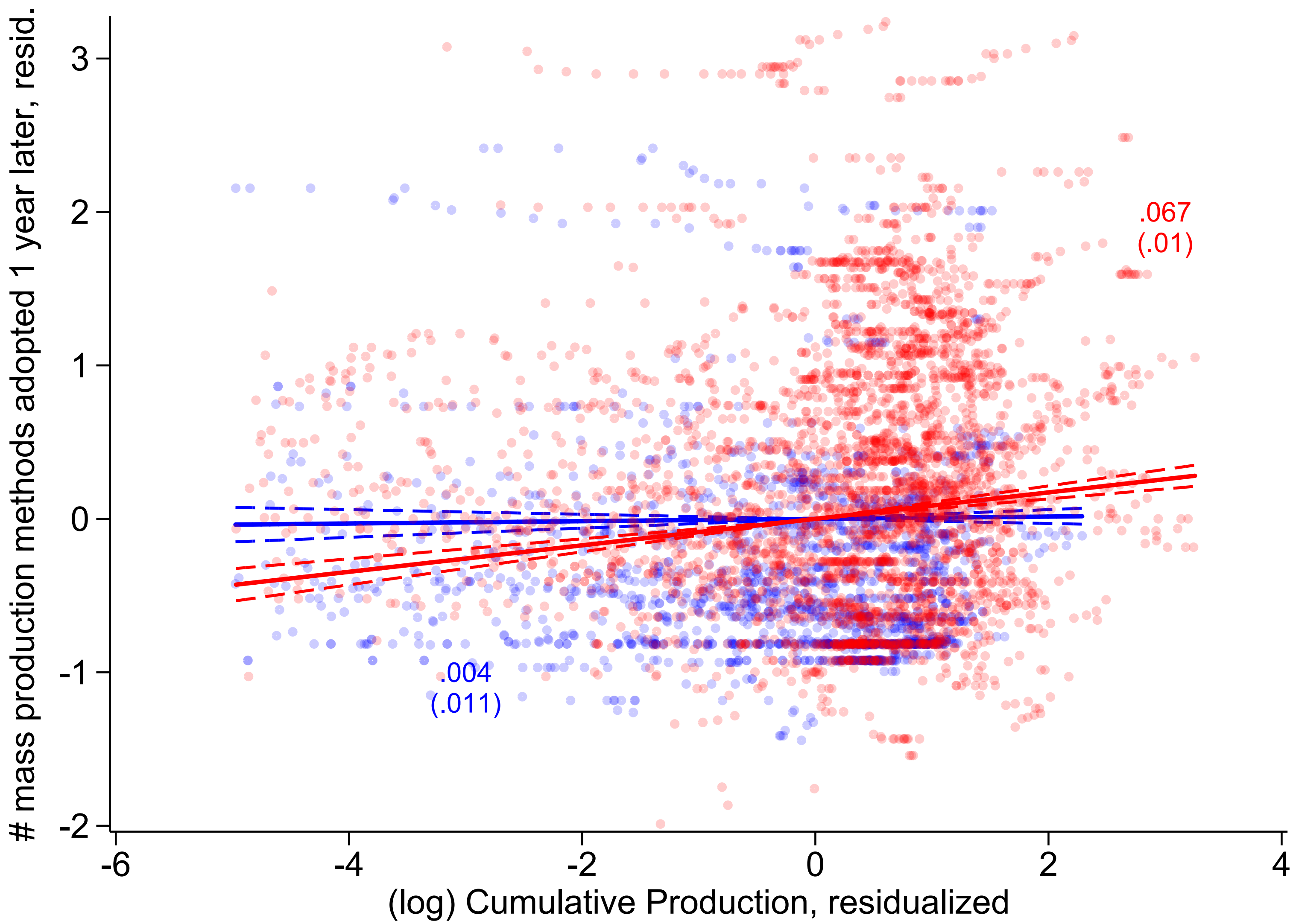
(b) Response to Cumulative Production to horizon h

(c) Controlling for Production in Months $t+1$ to $t+h$

(d) Controlling for Production in Months $t+1$ to $t+h$

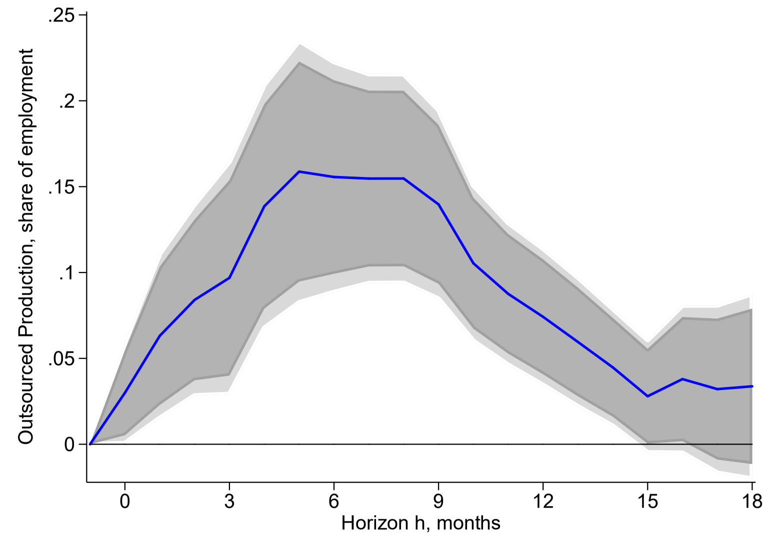
Note: The figure shows the response of TFP (adjusted for capital utilization) to a one percent shock to aircraft demand: local projections estimates of (6). Panels on the left-hand side show responses in the average plant: the β_h^{LBD} coefficients when $\beta_h^{LBN} = 0$ is imposed in (6). Panels on the right-hand side show responses in plants with above median initial capital utilization relative to those with below median utilization: β_h^{LBN} in an unrestricted version of (6). Aircraft demand and its interaction with initial capacity utilization are jointly predicted by the instrument described in Section 3, and its interaction with initial capacity utilization. In the top-row panels, the explanatory variable is the cumulative growth (log difference) of aircraft produced from month $t-1$ to month $t+h$. The estimates represent the percent growth in productivity at horizon h per one percent of cumulative growth in production up to that horizon, as predicted by the instrument at horizon zero. Responses in the bottom row follow Dube *et al.* (2023) and are the response of TFP to a once percent increase in demand at horizon zero, as predicted contemporaneously by the instrument, but include separate controls for production in each month t to $t+h$. The responses reflect the response of TFP to a one percent relative increase in demand at horizon zero, if that plant had experienced no further relative growth in total production to horizon h. Shaded areas show 90% and 95% Newey-West confidence intervals. First stage F-statistic at 12-month horizon = 130, 48, 28, and 14 in panels (a) to (d).

Figure 10: Adoption of Mass-Production Methods by Cumulative Production and Capital Utilization

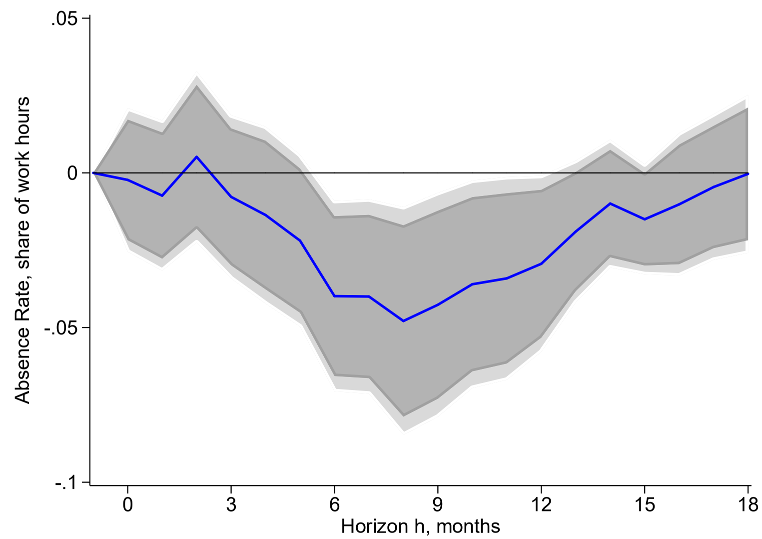


Note: The figure shows the number of mass production methods adopted (with a one-year lag) against the (log of) cumulative production in a production line. Both variables are residualized from monthly, plant, and aircraft model fixed effects. Red dots represent plants that had above median capital utilization at the beginning of the war and blue dots represent plants with below median capital utilization. Fitted regression lines for the two sub-samples are shown in solid lines, with 95% confidence intervals in dashed lines. Coefficients and standard errors for these regression lines are shown. There is a statistically significant association between cumulative production and subsequent adoption of mass-production methods for plants with high capital utilization, but no relationship for plants with low utilization. Source: USAAF (1952), Vol. 1, Table 3 and the author.

Figure 11: Responses to a 1% Shock to Aircraft Demand in High Utilization Plants (relative to Low)



(a) Outsourcing



(b) Absence Rate

Note:The figure shows responses of variables to a one percent shock to aircraft demand in plants with above median initial capital or labor utilization relative to those with below median utilization: the β_h^{LBN} coefficients in (6). Aircraft demand and its interaction with initial capacity utilization are jointly predicted by the instrument described in Section 3, and its interaction with initial capacity utilization. Panel (a) shows the response of the share of hours worked outsourced to feeder plants in high vs. low (initial) capital utilization plants. Panel (b) shows the response of the share of hours lost to absenteeism in high vs. low (initial) hours per worker plants. Shaded areas show 95% Newey-West confidence intervals. First stage F-statistic at 12-month horizon = 13 and 6, in the top and bottom panels, respectively.

Table 1: Summary Statistics

	Mean	Min	P10	P25	Median	P75	P90	Max	Coef. Var.
Panel A: Firm-level statistics									
# of plants	1.6	1	1	1	1	2	3	7	0.85
Models Produced	2.8	1	1	1	1	3	8	12	1.04
Total Sales (USD 1000)	713,575	4,710	14,823	26,896	153,371	1,193,764	2,221,488	3,675,244	1.43
Observations:	38								
Panel B: Plant-level statistics									
	Mean	Min	P10	P25	Median	P75	P90	Max	Coef. Var.
# of models	2.0	1	1	1	1	2	4	8	0.75
Peak production employment	10,170	373	621	1,599	6,977	15,182	24,034	48,128	1.03
Avg. Monthly Production (1000 Lbs.)	992.0	8.0	25.7	76.2	480	1,471	2,404	5,497	1.22
Cum. Investment ($1000)	19,328	276	276	1,447	12,141	31,151	48,658	94,898	1.10
Peak Floor Space (1000 sq. feet)	1,598	72	165	444	1,265	2,443	3,485	6,206	0.85
Observations:	61								
Panel C: Production-line-level statistics									
Peak Employment	7,465	55	481	1,465	4,556	9,818	16,021	125,360	1.63
Avg. Monthly Planes	61.0	0.50	2	11.3	36	83.8	160.6	339.1	1.10
Avg. Monthly Production (1,000s lbs.)	605.8	3.4	13.2	44.9	272.9	919.1	1,906	4,933	1.31
Observations:	141								

Note: Summary statistics of US World War II airframe industry. Sources: USAAF (1952) Vol. 1 Table 1 (production volume and weight) and Vol. 2 Tables 5 (floor space) and 6 (employment); "War Manufacturing Facilities Authorized by State and County," War Production Board Program and Statistics Bureau, June 15, 1945, RG 179, box 984, NARA College Park (investment); Civilian Production Administration (1945) (sales).

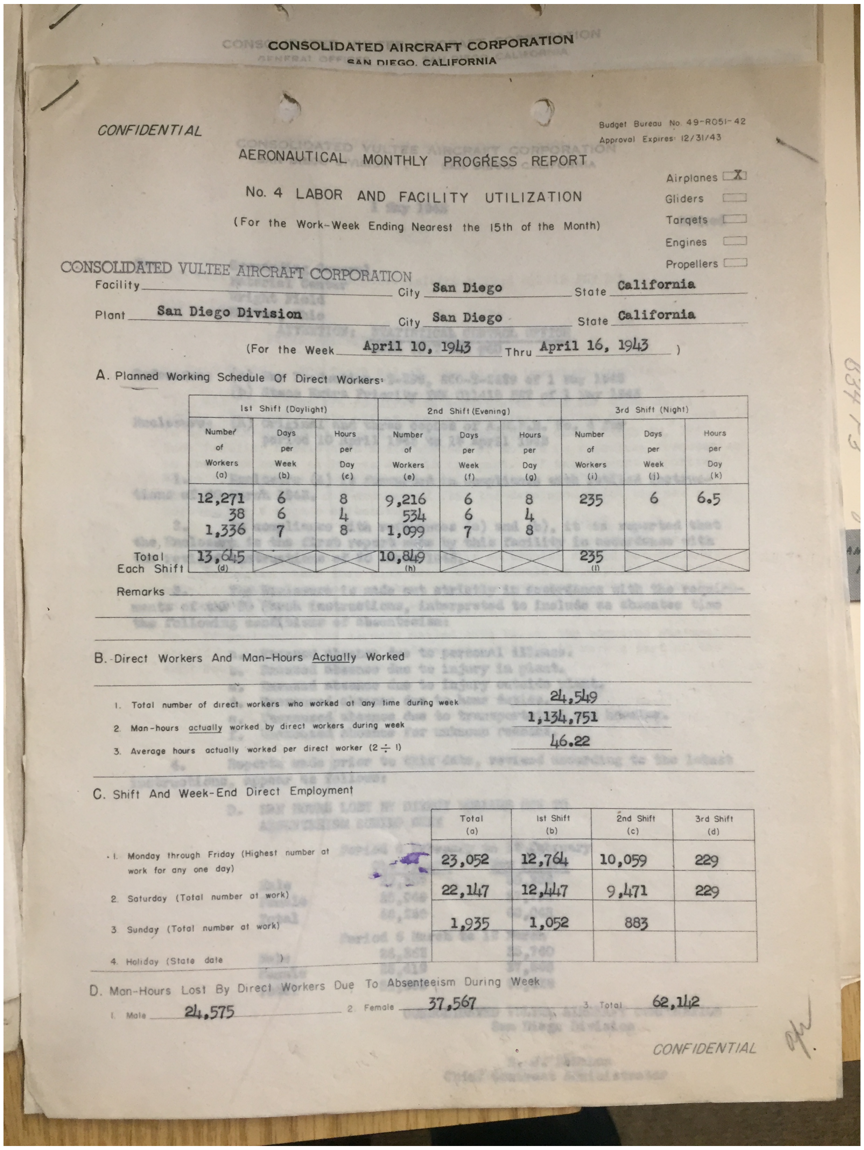
Online Appendix

Learning by Necessity:
Government Demand, Capacity Constraints, and Productivity Growth

Ethan Ilzetzki

A Appendix Figures & Tables (For Online Publication)

Figure A.1: AMPR Form Filled by an Airframe Manufacturer



CONSOLIDATED AIRCRAFT CORPORATION
SAN DIEGO, CALIFORNIA

CONFIDENTIAL

Budget Bureau No. 49-R051-42
Approval Expires: 12/31/43

AERONAUTICAL MONTHLY PROGRESS REPORT

No. 4 LABOR AND FACILITY UTILIZATION

(For the Work-Week Ending Nearest the 15th of the Month)

Airplanes [X]
Gliders [ ]
Targets [ ]
Engines [ ]
Propellers [ ]

CONSOLIDATED VULTEE AIRCRAFT CORPORATION
Facility ______ City San Diego State California
Plant San Diego Division City San Diego State California
(For the Week April 10, 1943 Thru April 16, 1943)

A. Planned Working Schedule Of Direct Workers:

	1st Shift (Daylight)			2nd Shift (Evening)			3rd Shift (Night)		
	Number of Workers (a)	Days per Week (b)	Hours per Day (c)	Number of Workers (e)	Days per Week (f)	Hours per Day (g)	Number of Workers (i)	Days per Week (j)	Hours per Day (k)
	12,271	6	8	9,216	6	8	235	6	6.5
	38	6	4	534	6	4			
	1,336	7	8	1,099	7	8			
Total Each Shift	13,645 (d)			10,849 (h)			235 (l)		

Remarks ______

B. Direct Workers And Man-Hours Actually Worked

1. Total number of direct workers who worked at any time during week 24,549
2. Man-hours actually worked by direct workers during week 1,134,751
3. Average hours actually worked per direct worker (2 ÷ 1) 46.22

C. Shift And Week-End Direct Employment

	Total (a)	1st Shift (b)	2nd Shift (c)	3rd Shift (d)
1. Monday through Friday (Highest number at work for any one day)	23,052	12,764	10,059	229
2. Saturday (Total number at work)	22,147	12,447	9,471	229
3. Sunday (Total number at work)	1,935	1,052	883	
4. Holiday (State date)				

D. Man-Hours Lost By Direct Workers Due To Absenteeism During Week

1. Male 24,575 2. Female 37,567 3. Total 62,142

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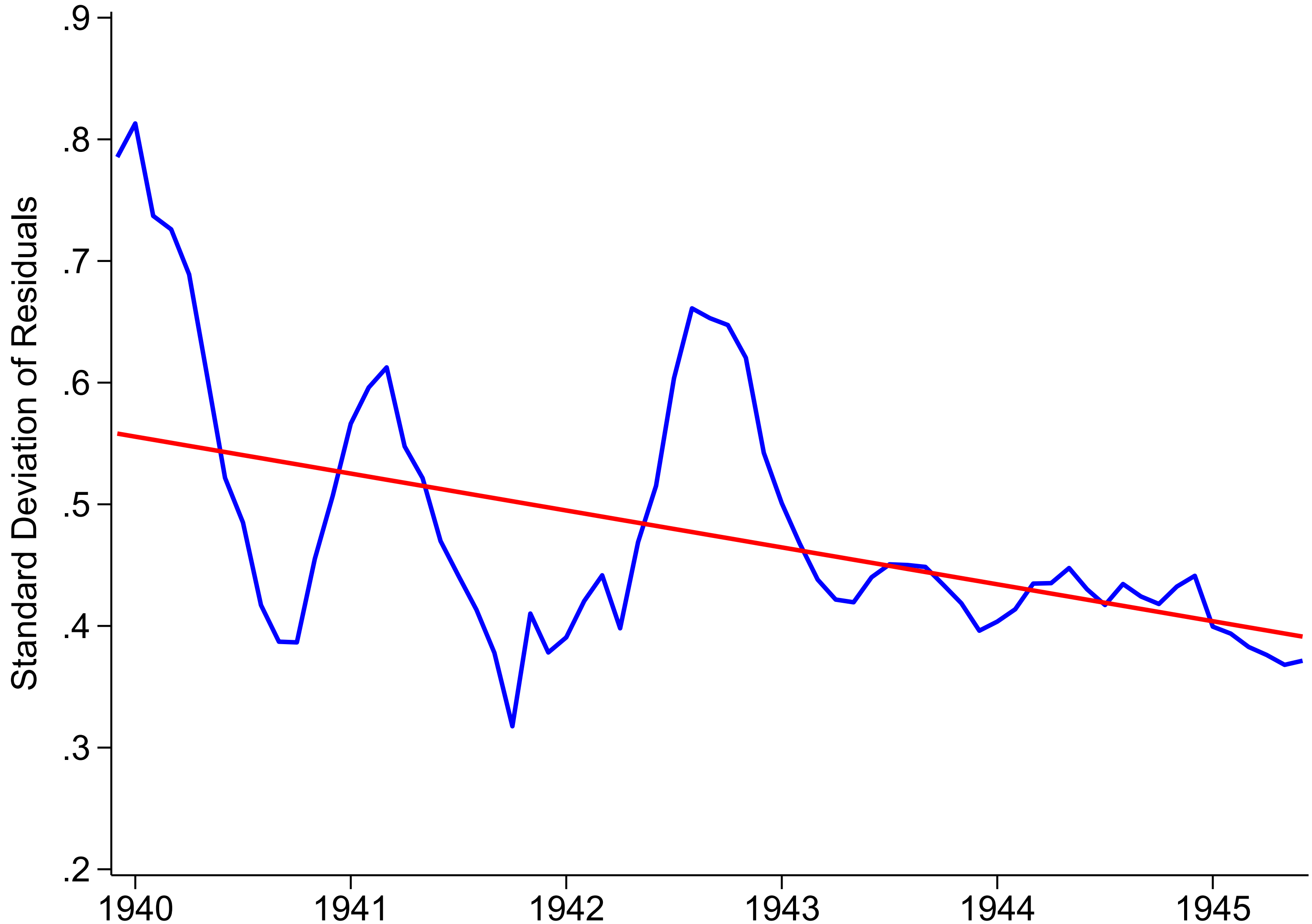
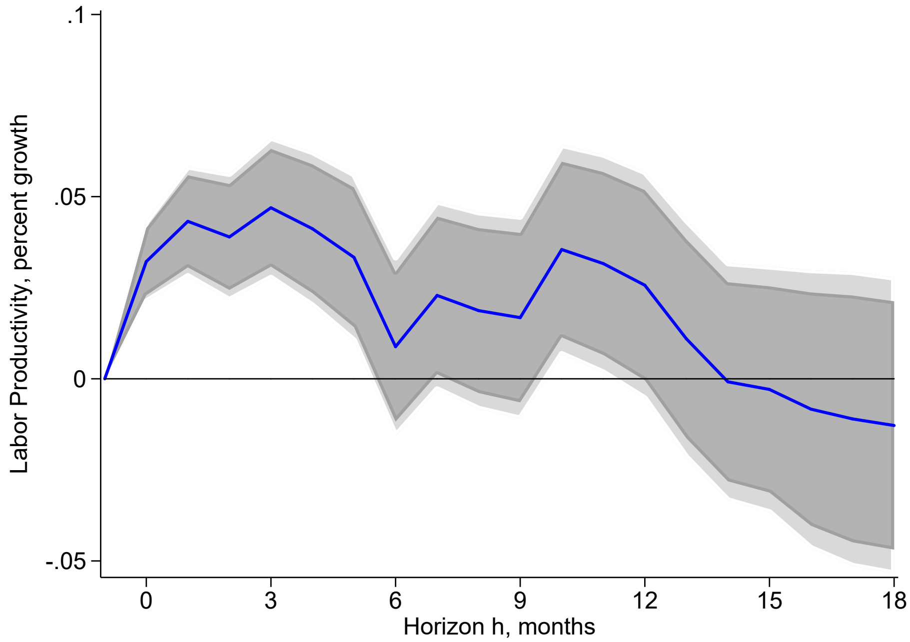
Note: Sample page from Aeronautical Monthly Progress Report (AMPR) form of Consolidated Vultee Aircraft Corporation, San Diego, in April 1943. This was a standardized form filled out by all aircraft manufacturers during the war. The sample comes from AMPR No. 4, which gives details on shift utilization. Source: Consolidated Vultee archives, San Diego Air and Space Museum, Box 34.

Figure A.2: Standard Deviation of (log) Aircraft Per Hour Worked Across Aircraft Plants

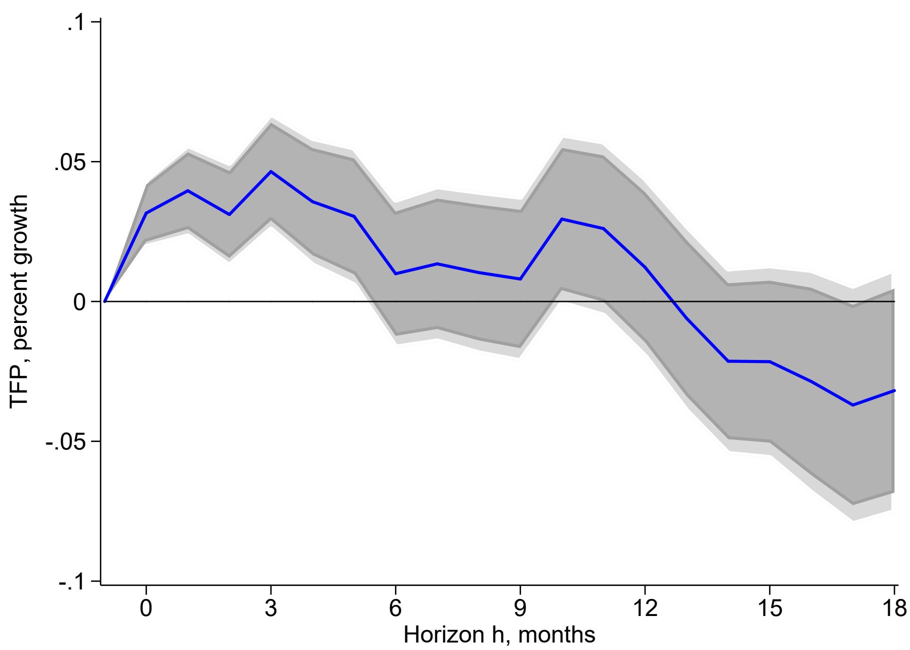


Note: The figure shows the standard deviation of log aircraft per hour worked (labor productivity) across airframe manufacturers in each month, 5-month moving average. Labor productivity is residualized from time and aircraft model fixed effects. The model fixed effects are crucial to absorb differences in aircraft per worker across aircraft models of varying size and complexity. Results are similar when excluding time fixed effects. Source: AMPR and the author.

Figure A.3: Response to a 1% Shock to Aircraft Demand (OLS)



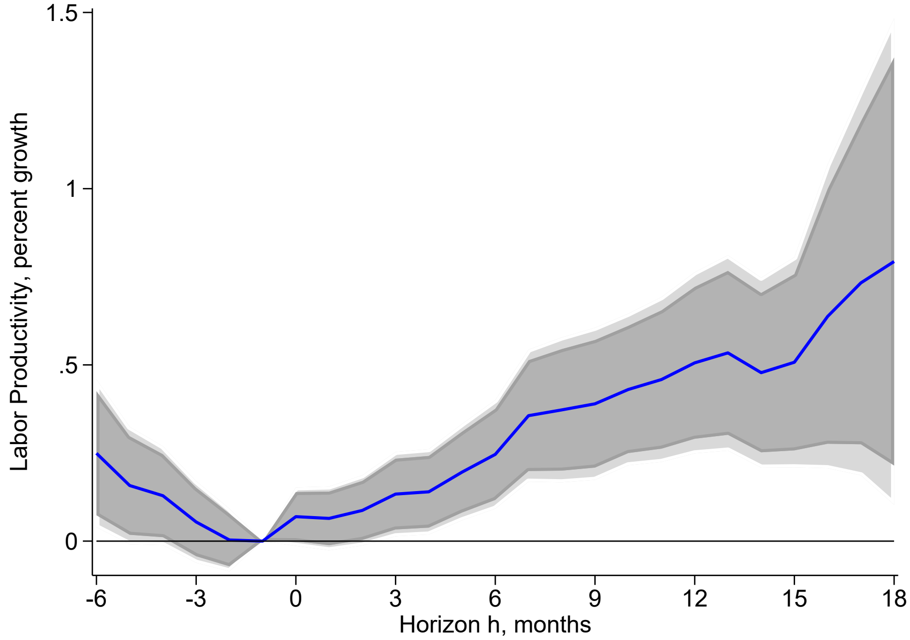
(a) Output per Hour Worked



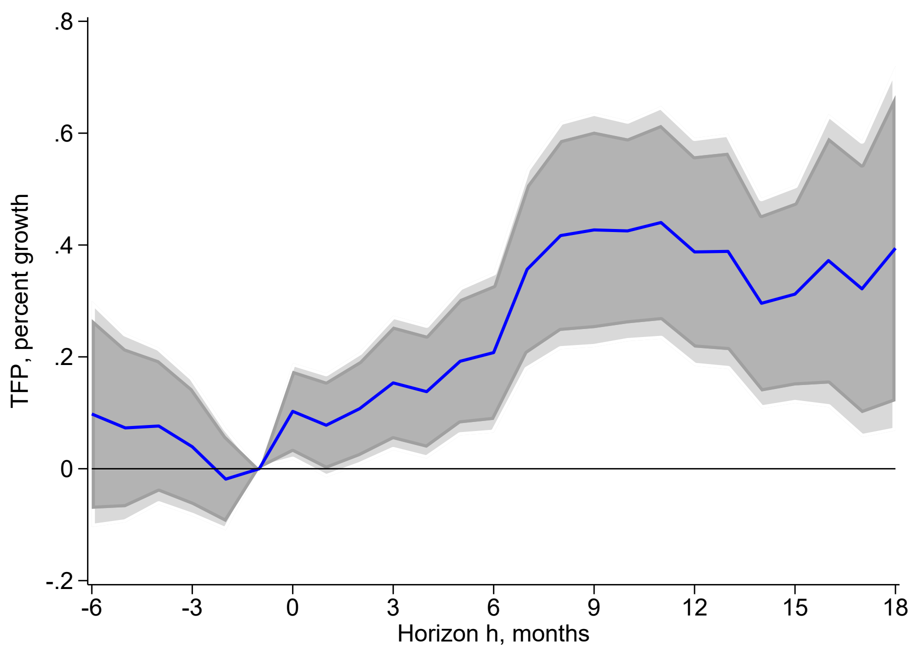
(b) TFP

Note: The figure shows the response of (a) log aircraft per hour worked and (b) TFP (adjusted for capital utilization). The shaded areas show 90% and 95% Newey-West confidence intervals. Responses are the β_h^{LBD} coefficients of OLS local projections estimates of (6), with $\beta_h^{LBN} = 0$ imposed.

Figure A.4: Pre-trends in Labor Productivity and TFP



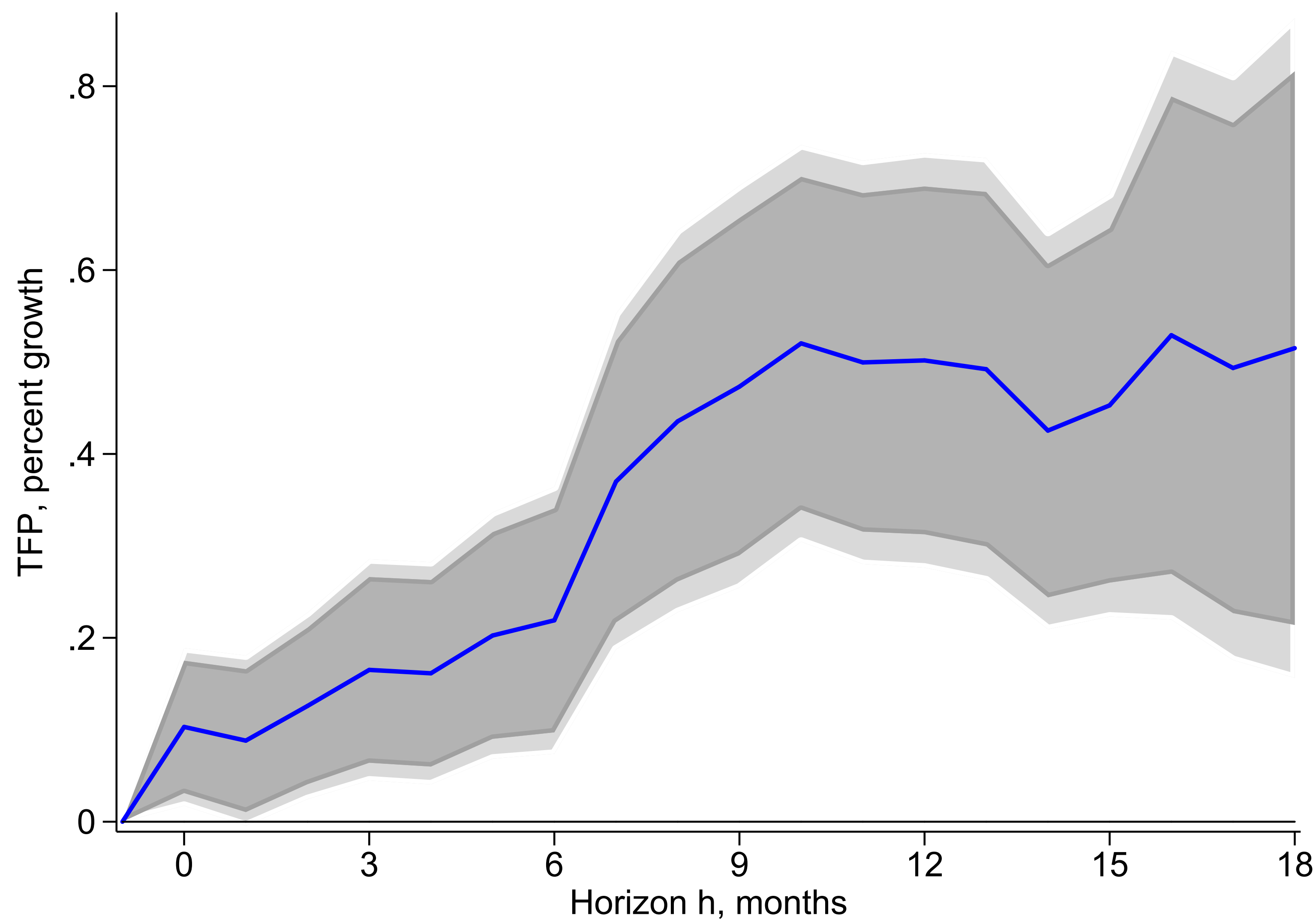
(a) Output per Hour Worked



(b) TFP

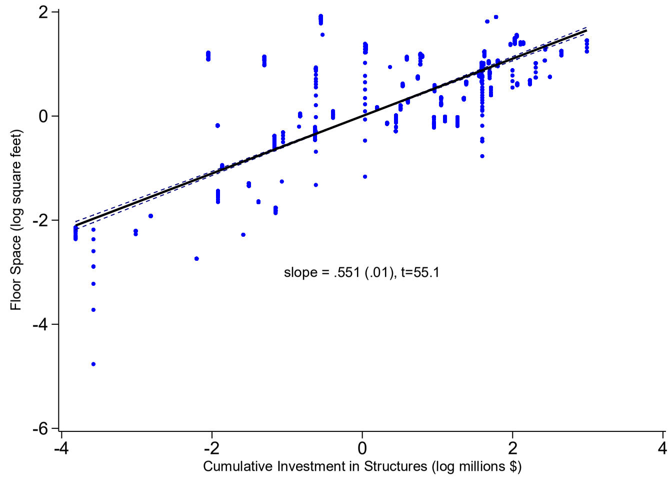
Note: The figure shows the response of (a) log aircraft per hour worked and (b) TFP (adjusted for capital utilization). Responses are the β_h^{LBD} coefficients of local projections estimates of (6), with $\beta_h^{LBN} = 0$ imposed. Aircraft demand is predicted by the instrument described in Section 3. Shaded areas show 95% Newey-West confidence intervals. First stage F-statistic at 12-month horizon = 24 and 30 in the two panels. Negative horizons are before the shock to demand and show pre-trends, evaluating differential trends of plants receiving a demand shock at time zero.

Figure A.5: Response of TFP (not adjusted for Capital Utilization) to a 1% Shock to Aircraft Demand

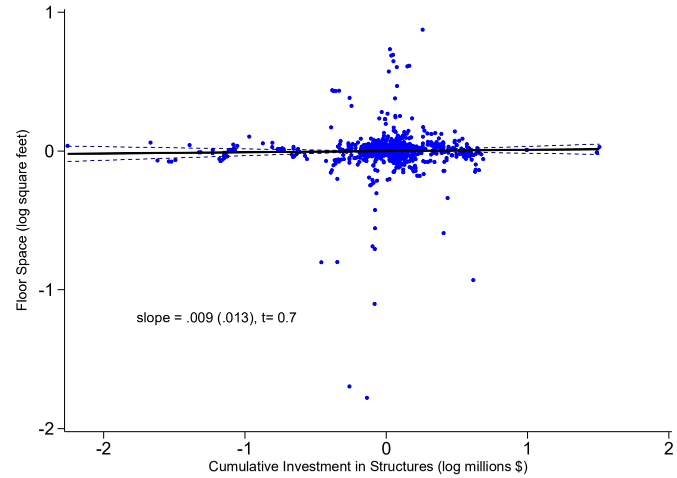


Note: The figure shows the response of TFP (not adjusted for capital utilization) to a one percent shock to aircraft demand. Estimates are based on local projections, with aircraft demand instrumented with the instrument described in Section 3, and laid out in (6). Shaded areas show 90% and 95% Newey-West confidence intervals. First stage F-statistic at 12-month horizon = 32.

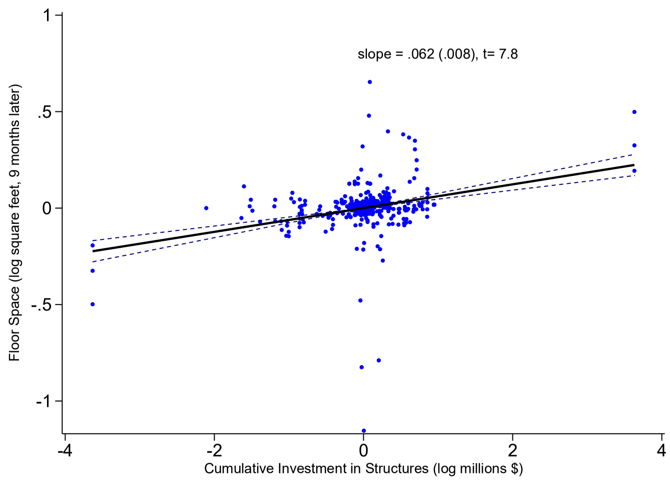
Figure A.6: Comparing Measures of Plant Capital



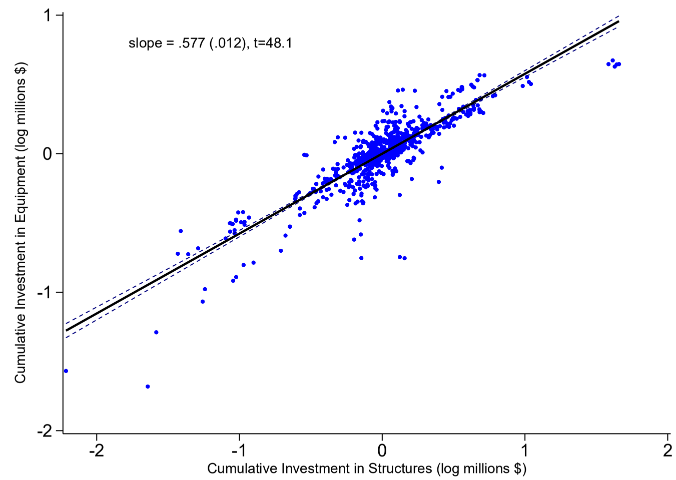
(a) Floor Space vs. Capital Investment in Structures



(b) Floor Space vs. Capital Investment in Structures with 2 way fixed effects



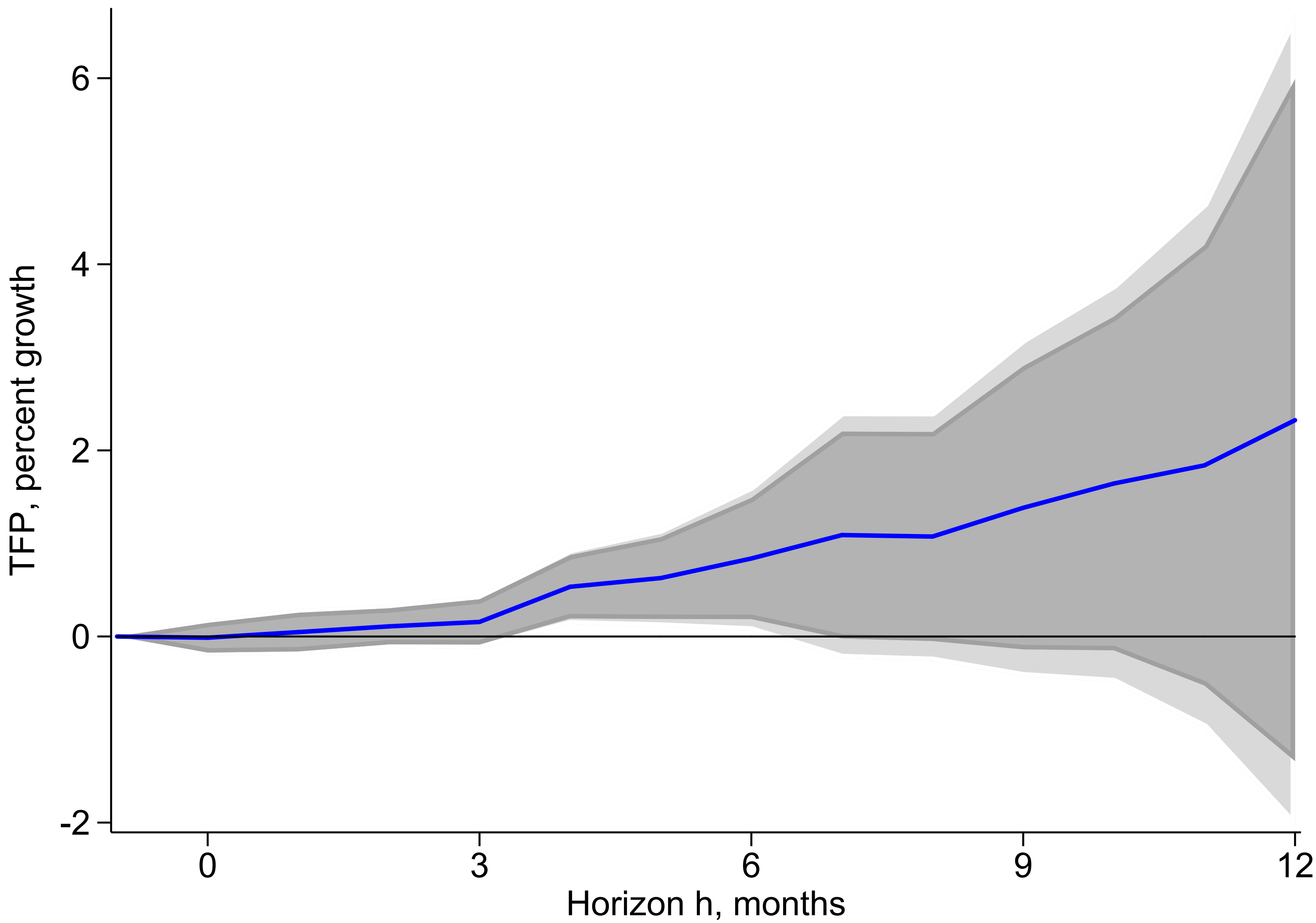
(c) Floor Space with 9 month lag vs. Capital Investment in Structures with 2 way fixed effects



(d) Capital Investment in Equipment vs. in Structures 2 way fixed effects

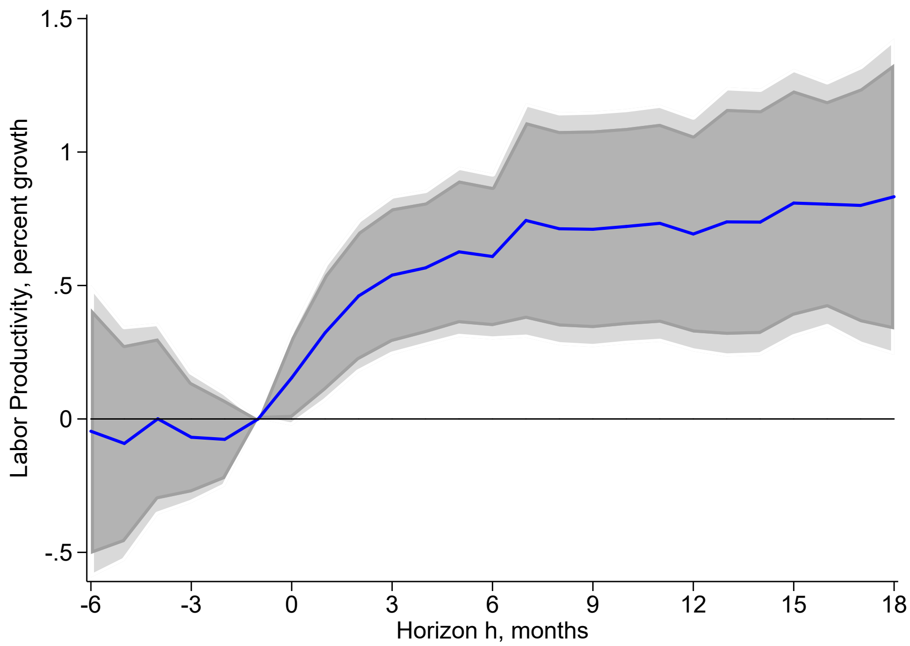
Note: Panel (a) shows a scatter plot of floor space in (log) square feet and cumulative investment in structures in (log) millions of US$. Each observation is a monthly reading of the two variables for a specific plant. Panel (b) shows the same figure residualized from monthly and plant fixed effects. The zero correlation in panel (b) means that the raw correlation in panel (a) is driven by plants having consistently different quantities of floor space and investment in structures over the war's duration; and by the across-the-board growth in both capital and in floor space over the duration of the war. Panel (c) then shows a scatter plot of current cumulative investment in structures and floor space in use *9 months later*. Despite two-way fixed effects there is a strong correlation between the two, reflecting that investments in structures only lead to increased floor space with a substantial lag. Panel (d) shows a strong contemporaneous correlation between cumulative capital investments in structures and capital investments in equipment. A 1% increase in the value of structures is associated with a 0.6% increase in the value of equipment. The figure is similar when looking at investment flows rather than cumulative stocks. Sources: USAAF (1952) Vol. 1, Table 5 and "War Manufacturing Facilities Authorized by State and County,"War Production Board Program and Statistics Bureau, June 15, 1945. RG 179, box 984, NARA College Park.

Figure A.7: Response of TFP to a 1% Shock to Aircraft Demand, Using Demand Shocks Only from First Half of Sample

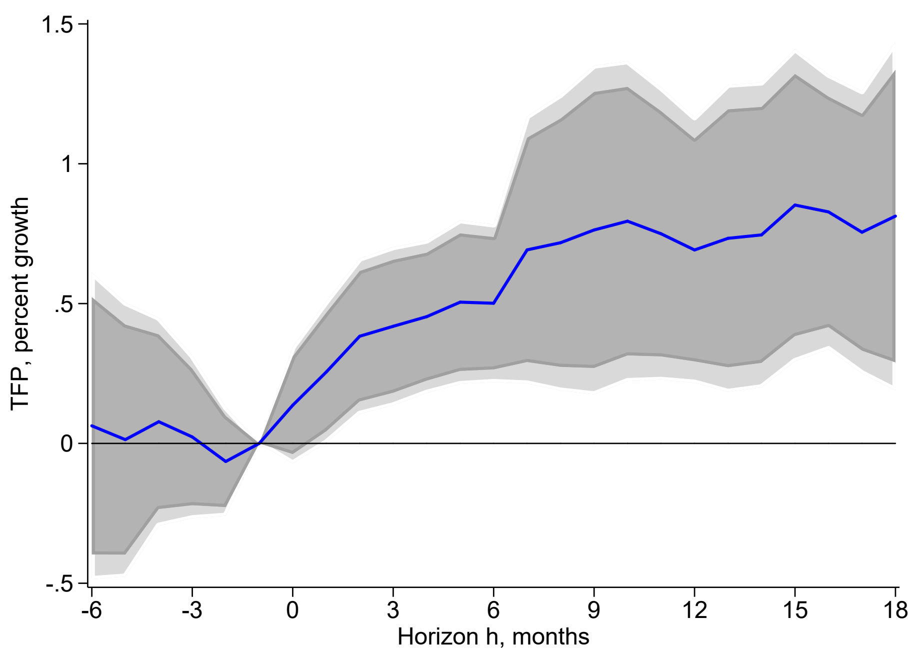


Note: The figure shows the response of TFP (not adjusted for capital utilization) to a one percent shock to aircraft demand. Estimates are based on local projections, with aircraft demand instrumented with the instrument described in Section 3, with estimating equation (6). The leave-one-out instrument is interacted with a dummy equaling one for months in the first half of the sample. This specification limits bias that could potentially arise when comparing plants receiving demand late in the war ("late treatment") with plants receiving demand early in the war ("early treatment") in months late in the war, following Goodman-Bacon (2021). Shaded areas show 90% and 95% Newey-West confidence intervals. First stage F-statistic at 5-month horizon = 7.5.

Figure A.8: Response of Productivity to a 1% Shock to Aircraft Demand in high vs. low capital utilization plants: Controlling for Plant Age



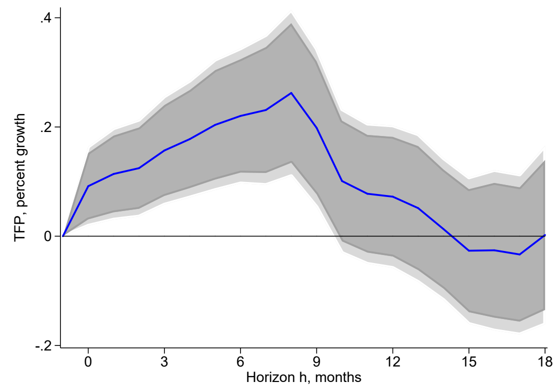
(a) Output per Hour Worked



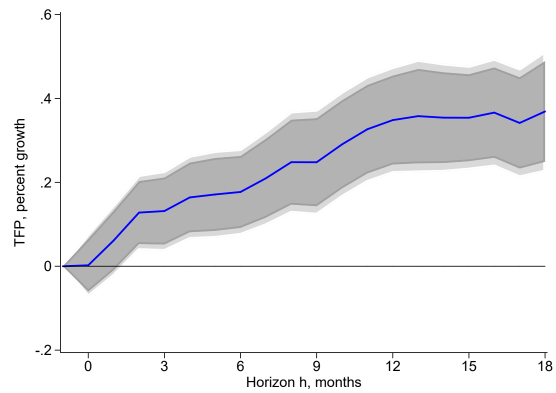
(b) TFP

Note: The figure shows responses of (a) (log) aircraft per hour worked and (b) TFP (adjusted for capital utilization) to a one percent shock to aircraft demand in plants with above median initial capital utilization relative to those with below median utilization. Responses are the the β_h^{LBN} coefficients of local projections estimates of (6). Aircraft demand and its interaction with initial capacity utilization are jointly predicted by the instrument described in Section 3 and its interaction with initial capacity utilization. The specification includes controls for plant age and the interaction between demand and a dummy equaling one if the plant was above median in age. Negative horizons are before the shock to demand and show pre-trends, evaluating differential trends of plants receiving a demand shock at time zero. Shaded areas show 90% and 95% Newey-West confidence intervals. First stage F-statistic at 12-month horizon = 3 in both panels.

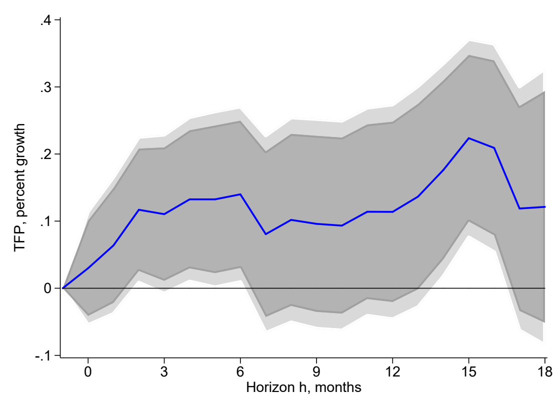
Figure A.9: Response of TFP to 1% Aircraft Demand Shock in Tight vs. Looser Labor Conditions



(a) Heterogeneity Based on Hours per Worker



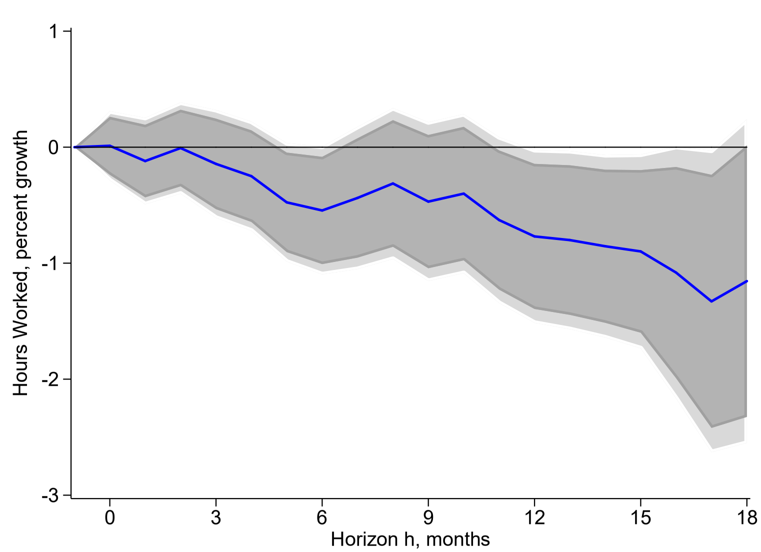
(b) Heterogeneity Based on Local Wages



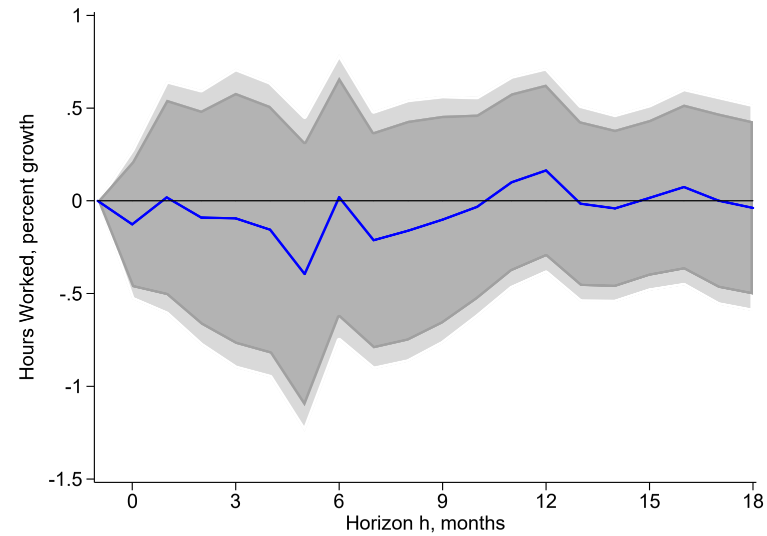
(c) Heterogeneity Based on War Manpower Commission Classification

Note: The figure shows responses of TFP to a one percent shock to aircraft demand in plants with tight labor conditions relative to those with looser labor conditions. Panel (a) shows response in plants that had above median hours per worker at the beginning of the war relative to those below the median. Panel (b) shows plants in labor markets with above median wages with our sample (wages were above the national median in most regions that had aircraft plants) at the beginning of the war relative to those below the median. Panel (c) shows plants in labor markets classified in group 1 (highest) labor market tightness by the War Manpower Commission at the beginning of the war, relative to those in categories 2-4. (Most aircraft plants were in labor markets classified in groups 1 and 2). Responses are the the β_h^{LBN} coefficients of local projections estimates of (6). Aircraft demand and its interaction with the indicators of labor market tightness are jointly predicted by the instrument described in Section 3 and its interaction with the labor market indicator. Shaded areas show 90% and 95% Newey-West confidence intervals. First stage F-statistic at 12-month horizon = 16, 17, and 12 in the three panels, respectively.

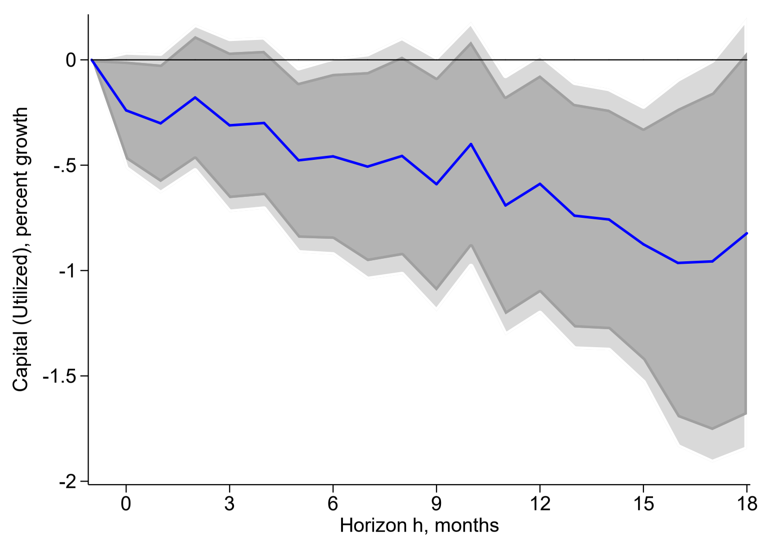
Figure A.10: Response of Factors of Production



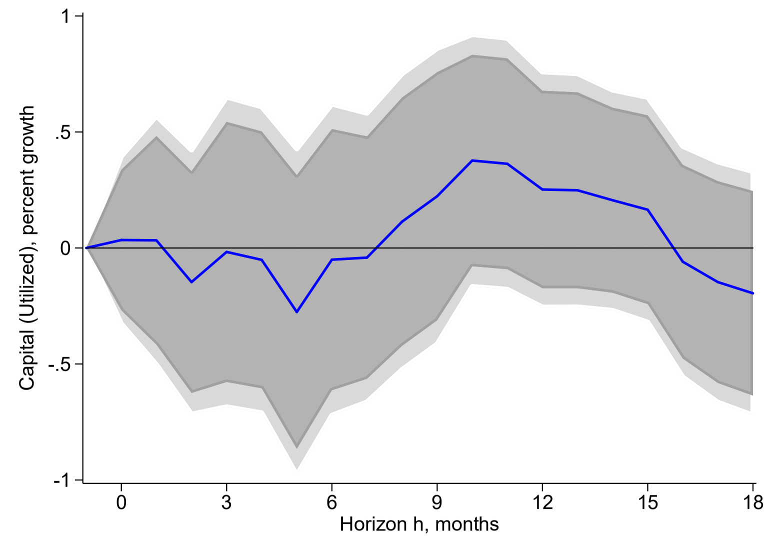
(a) Response of Labor, Hours



(b) Response of Labor, Hours, High vs. Low Capital Utilization Plants



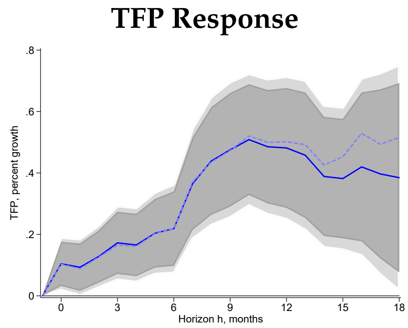
(c) Response of Utilization-Adjusted Capital



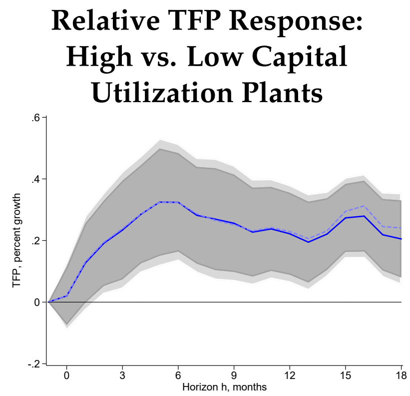
(d) Response of Utilization-Adjusted Capital, High vs. Low Capital Utilization Plants

Note: The figure shows the response of factors of production to a one percent shock to aircraft demand: local projections estimates of (6). Panels on the left-hand side show responses in the average plant: the β_h^{LBD} coefficients when $\beta_h^{LBN} = 0$ is imposed in (6). Panels on the right-hand side show responses in plants with above median initial capital utilization relative to those with below median utilization: β_h^{LBN} in an unrestricted version of (6). Aircraft demand and its interaction with initial capacity utilization are jointly predicted by the instrument described in Section 3, and its interaction with initial capacity utilization. In the top-row panels, the dependent variable is labor measured by (log) hours worked. In the bottom-row panels, the dependent variable is capital measured by (log) floor space multiplied by capital utilization, measured through shift utilization. Shaded areas show 90% and 95% Newey-West confidence intervals. First stage F-statistic at 12-month horizon = 28, 15, 34 and 16 in panels (a) to (d).

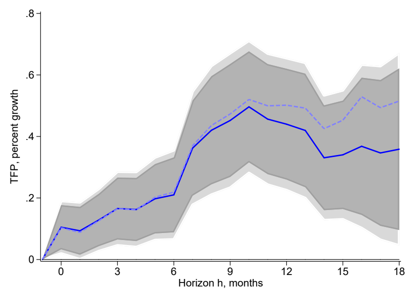
Figure A.11: Controlling for Spillovers from Peer Production Lines



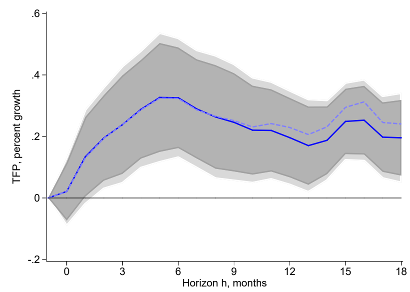
(a) Control: Average Productivity Growth of All Other Production Lines Producing Same Broad Type



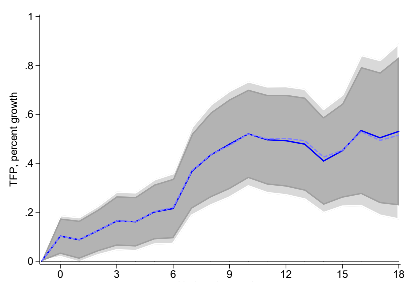
(b) Control: Average Productivity Growth of All Other Production Lines Producing Same Broad Type



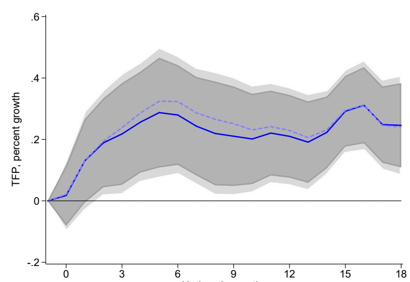
(c) Control: Average Productivity Growth of All Other Production Lines Using the Same Motor Manufacturer



(d) Control: Average Productivity Growth of All Other Production Lines Using the Same Motor Manufacturer



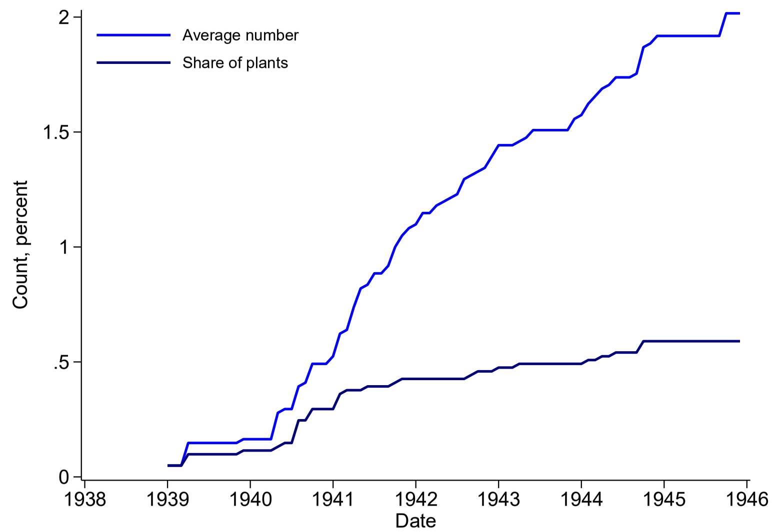
(e) Control: Average Production of All Other Production Lines Using the Same Motor Manufacturer



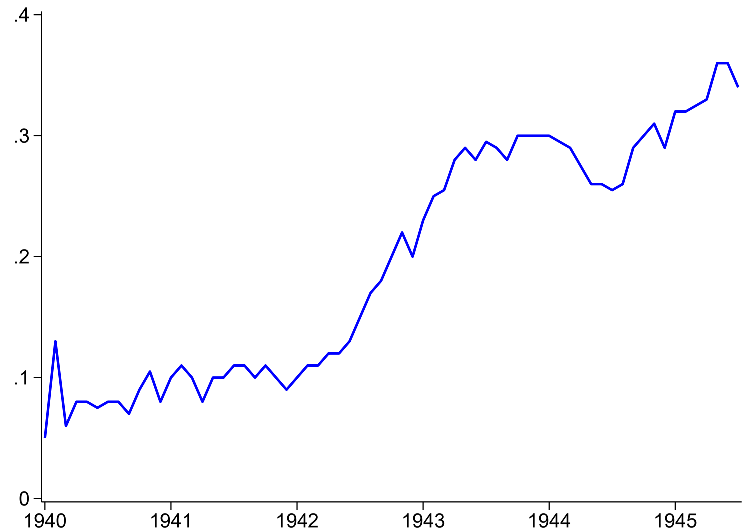
(f) Control: Average Production of All Other Production Lines Using the Same Motor Manufacturer

Note: The figure shows the response of TFP to a one percent shock to aircraft demand: local projections estimates of (6). Panels on the left-hand side show responses in the average plant: the β_h^{LBD} coefficients when $\beta_h^{LBN} = 0$ is imposed in (6). Panels on the right-hand side show responses in plants with above median initial capital utilization relative to those with below median utilization: β_h^{LBN} in an unrestricted version of (6). Aircraft demand and its interaction with initial capacity utilization are jointly predicted by the instrument described in Section 3, and its interaction with initial capacity utilization. Specifications in the top row include a control for the average growth in labor productivity for all production lines producing the same broad aircraft type excluding the production line studied, from month $t-1$ to month $t+h$. Specifications in the middle row include a control for the average growth in labor productivity for all production lines using the same motor manufacturer, excluding the production line studied, from month $t-1$ to month $t+h$. Specifications in the bottom row include a control for the number of airframes produced in all production lines producing using the same motor manufacturer, excluding the production line studied, in month t . Shaded areas show 90% and 95% Newey-West confidence intervals. Dashed lines show the regression coefficients in the baseline regressions without controls, as in Figures 6 and 7 First stage F-statistic at 12-month horizon = 29, 15, 30, 14, 32, and 16 in panels (a) to (f), respectively.

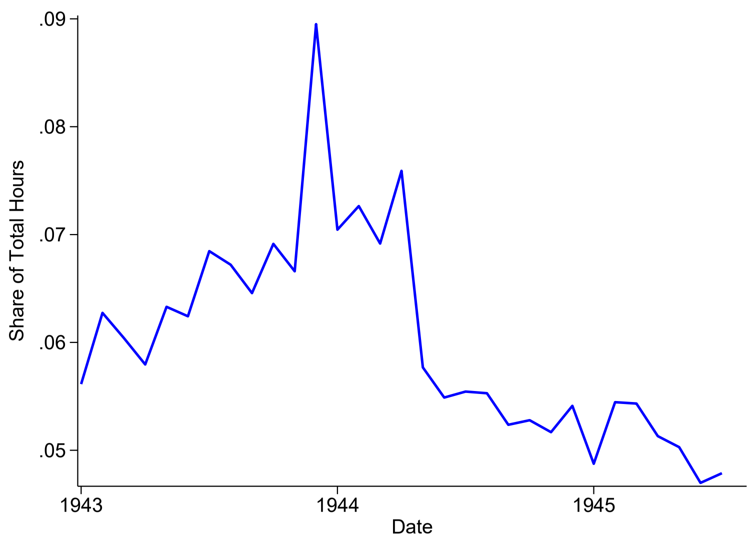
Figure A.12: Factors Affecting Productivity in Airframe Plants (Time Series)



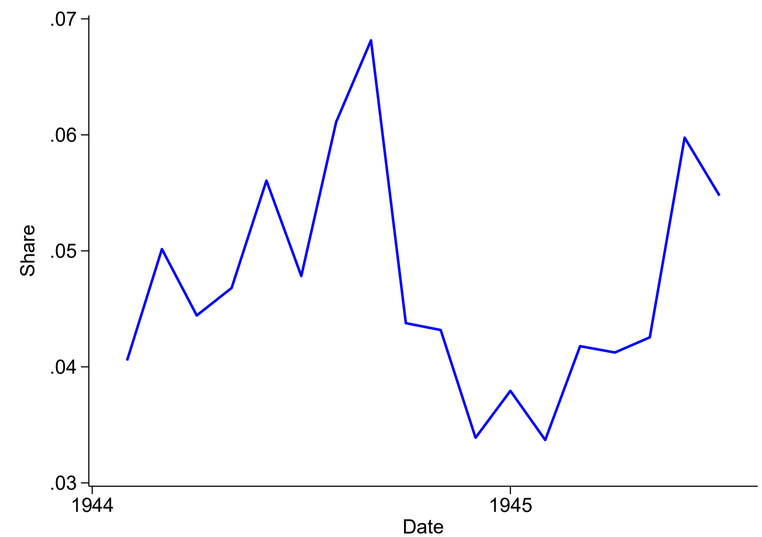
(a) Mass Production Methods Adopted:
share of plants and average number



(b) Outsourcing (average share of hours)



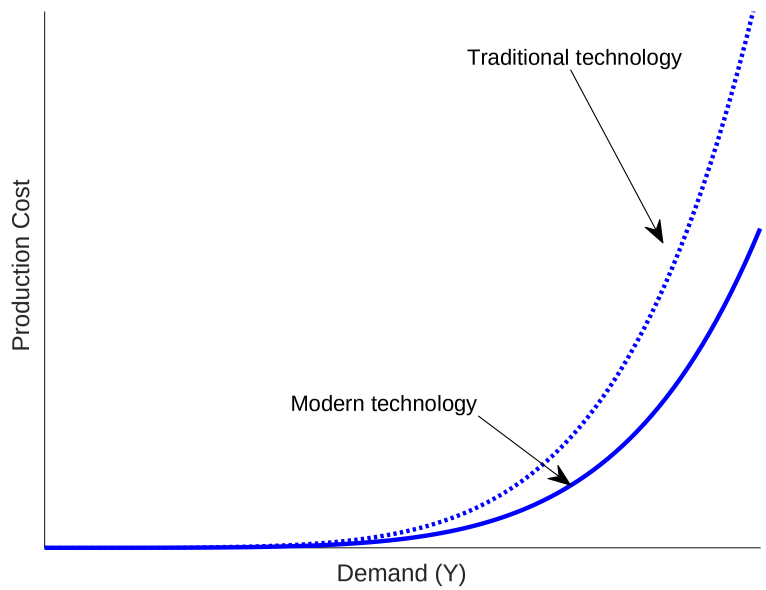
(c) Absenteeism



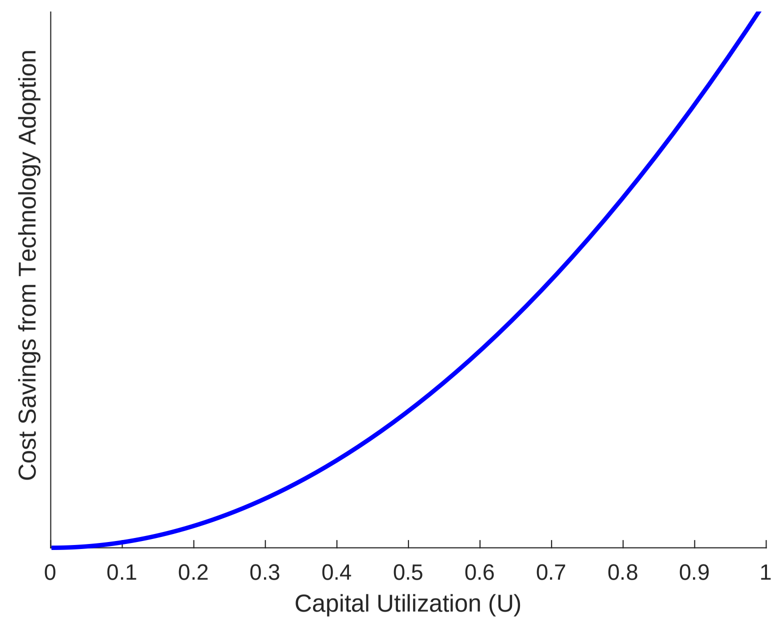
(d) Quit Rates

Each panel shows one statistic that has been suggested to have affected productivity in airframe plants during World War II. Panel (a) shows the cumulative share of plants (lower line) adopting mass production methods and the number of methods adopted by the average plant (top line). Source: Newspaper reports, corporate annual reports, and the author, as described in Section 5. Panel (b) shows the share of work hours in the assembly of aircraft that were outsourced to feeder plants from the median airframe plant. Source: USAAF (1952) Vol. 1, Table 3. Panel (c) shows the share of worker-hours lost due to worker absence in the median plant. Panel (d) gives the quit rate, the percent of workers quitting, in the median plant. Sources: Bureau of Labor Statistics, "Labor Statistics for the Aeronautical Industry," Reel 2237, PDF pp. 2210-2284; and Army Air Force Material Command, "Aircraft Program Progress Report," several volumes, Reel 2237, PDF pp. 2285-2648; both from the archives of the Air Force Historical Research Agency, Maxwell Air Force Base, AL

Figure A.13: Cost Curves in a Theory of Learning by Necessity



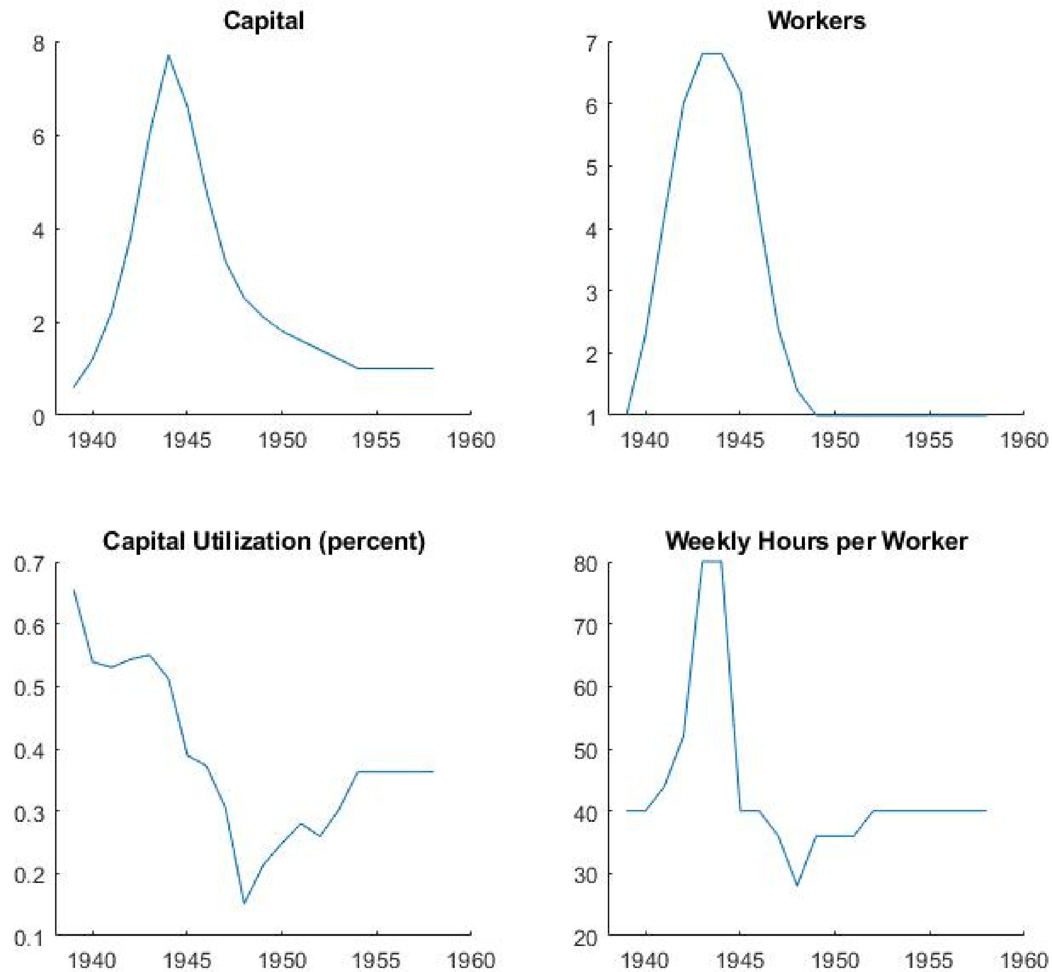
(a) Utilization Cost as a Function of Demand



(b) Cost Savings due to Technology Adoption, by Utilization

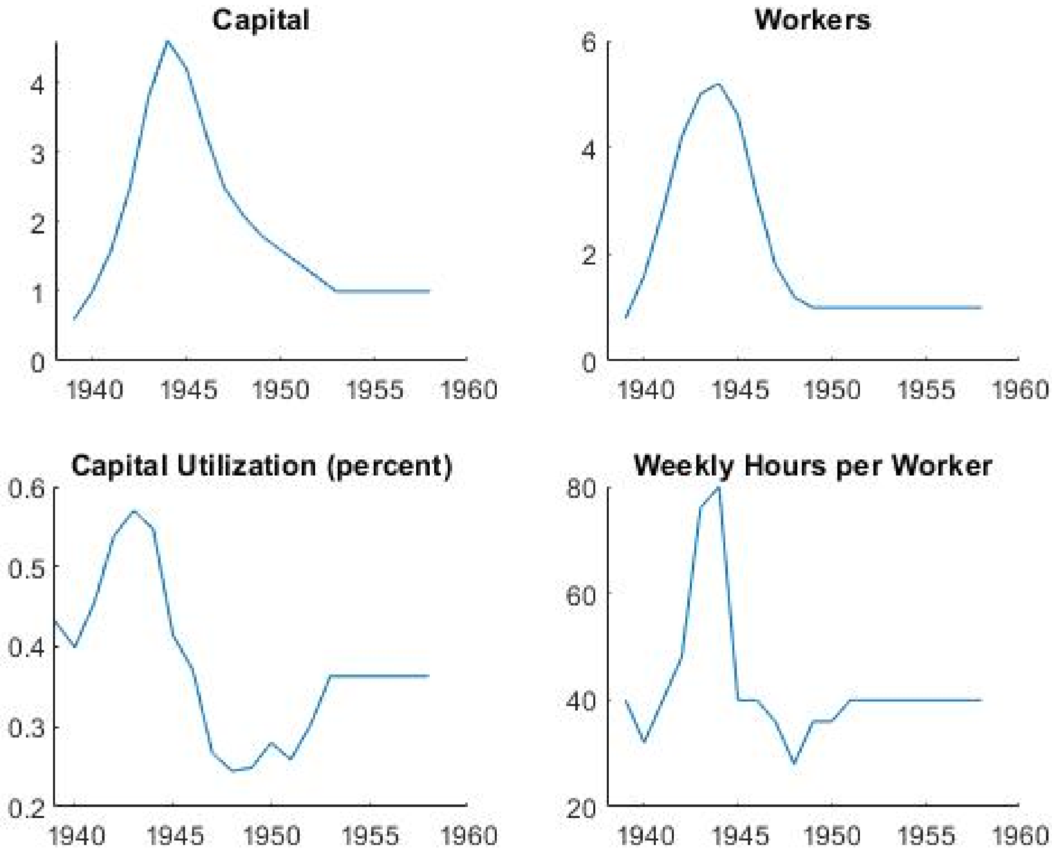
Note: The panels show cost curves arising from the theory of learning by necessity outlined in Appendix B. Panel (a) shows production (utilization) costs as a function of demand Y. The top curve represents a cost function using a traditional technology with TFP of z^T. The bottom curve represents a cost function using a modern technology with TFP of $z^M > z^T$. The gap between the curves gives the (gross) cost savings obtained if the modern technology is adopted. While the X-axis shows demand, what matters is demand relative to (maximal) production capacity. Panel (b) shows the cost savings of modern technology adoption as a function of capital utilization. Utilization is endogenous, but uniquely determined by–and monotonically increasing in–demand relative to existing capacity.

Figure A.14: Model Simulation: Average Plant



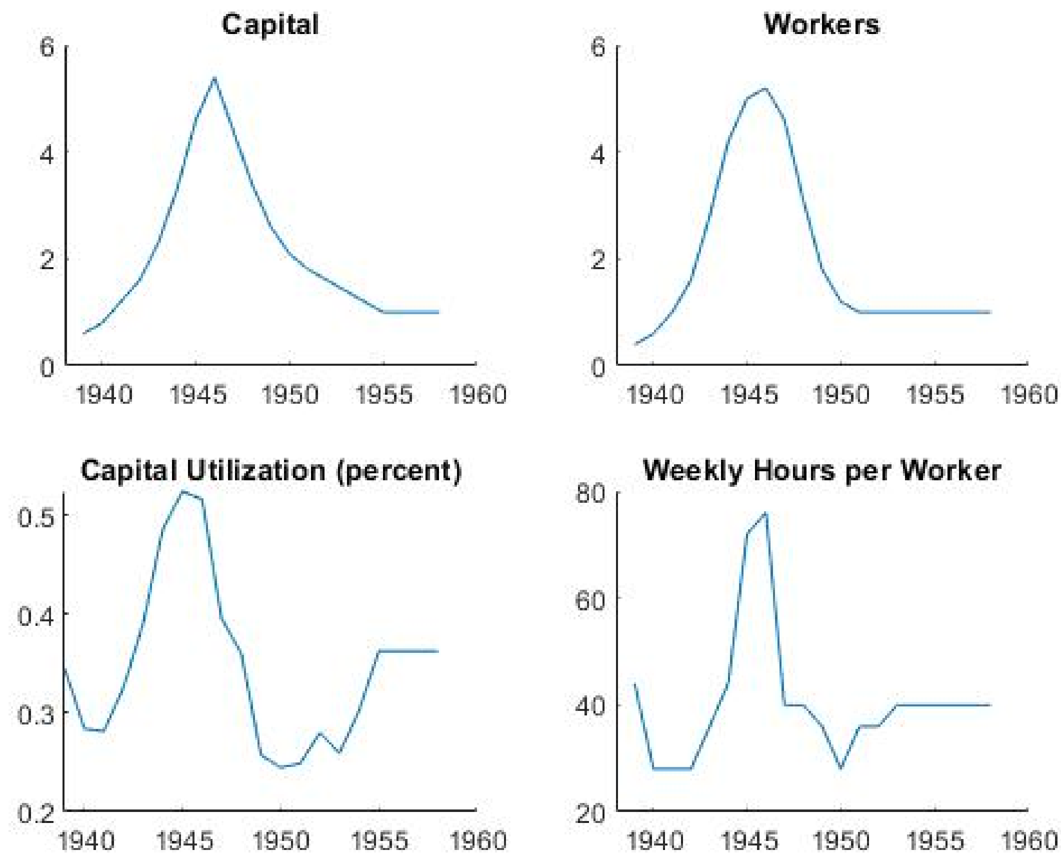
Model response of a plant to an unanticipated increase in demand announced in 1938, and matched to the production path of the average airframe plant in World War II. Full model presented in Appendix B. The top panels give the capital stock and number of workers as a multiple of the post-war steady state (calibrated to match the average of 1944-48 in the data). The bottom two panels give capital utilization in percent and hours per worker (in hours).

Figure A.15: Model Simulation: Low Demand Plant



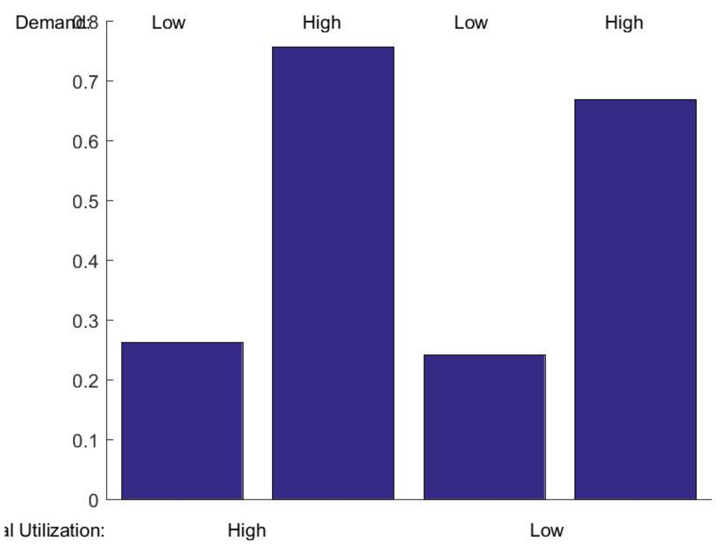
Model response of a plant to an unanticipated increase in demand announced in 1938, and matched to the production path of 25th percentile plant ("low demand"). Full model presented in Appendix B. The top panels give the capital stock and number of workers as a multiple of the post-war steady state (calibrated to match the average of 1944-48 in the data). The bottom two panels give capital utilization in percent and hours per worker (in hours).

Figure A.16: Model Simulation: Low Capacity Utilization Plant

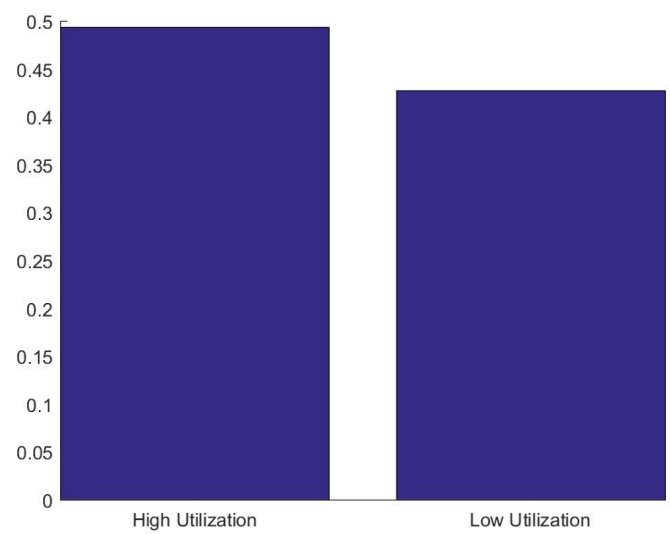


Model response of a plant to an unanticipated increase in demand announced in 1938, and matched to the production path of the average plant, but postponed by two years, reflecting a plant whose demand peaked in 1945 rather than 1943. This matches the utilization rate of the 25th percentile plant. Full model presented in Appendix B. The top panels give the capital stock and number of workers as a multiple of the post-war steady state (calibrated to match the average of 1944-48 in the data). The bottom two panels give capital utilization in percent and hours per worker (in hours).

Figure A.17: Cost Savings from Technology Adoption: Model Results



(a) Cost Savings



(b) Difference in Cost Savings

Panel (a) gives the cost savings achieved from adopting a technology that increases TFP by 35% in the model of Appendix B. Savings are given as a fraction of the net present value of all variable costs over the 100 years of model simulation. The four scenarios, from left to right, are high initial utilization and low demand; high initial utilization and high demand; low initial utilization and low demand; low initial utilization and high demand. High and low demand and high and low utilization are set to match the 25th and 75th percentiles, respectively, of these two variables. Panel (a) gives the difference between the high demand and low demand cases (as a percent of the NPV of costs) for the high (left bar) and low (right bar) utilization scenarios. These are the differences between the second and first bars and the fourth and third bars, respectively.

Table A1: Robustness Checks: Labor Productivity and TFP Responses

Dependent Variable: log Aircraft per Hour Worked

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
log Aircraft Demand	0.026	0.506***	0.506***	0.421***	0.532***	0.506***	0.416***
	(0.017)	(0.131)	(0.111)	(0.098)	(0.172)	(0.131)	(0.096)
Observations	958	958	847	942	944	958	958
Adjusted R^2	0.705	0.423	0.449	0.570	0.402	0.423	0.459
First Stage F-stat		24.7	32.5	38.5	15.4	24.7	47.3

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Dependent Variable: TFP

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
log Aircraft Demand	0.015	0.502***	0.537***	0.435***	0.549***	0.502***	0.379***
	(0.017)	(0.115)	(0.119)	(0.091)	(0.162)	(0.115)	(0.078)
Observations	867	867	859	852	861	867	867
Adjusted R^2	0.712	0.417	0.354	0.540	0.356	0.417	0.508
First Stage F-stat		32.1	31.9	46.6	18.3	32.1	70.8

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: Regression results showing the response of labor productivity (top panel) and TFP (bottom panel) to a 1% increase in aircraft demand. Coefficients are the β_{12}^{LBD} coefficients of local projections estimates of (6), with $\beta_{12}^{LBN} = 0$ imposed. Column 1 shows an OLS specification, as in Figure A.3 in the appendix. Column 2 uses (and the remaining columns use) IV, with aircraft demand predicted by the instrument described in Section 3. Column 3 controls for the growth of factors of production from time $t-1$ to $t+12$, as in Figure 8. Column 4 controls for (log) cumulative production, or "experience". Column 5 controls for cumulative capital investment in equipment. Column 6 controls for plant age. Column 7 weights observations by each plant's total production over the duration of the war. Anderson-Rubin p-stat < 0.01 in all specifications.

Table A2: Robustness: Heterogeneity with Capacity Utilization

Dependent Variable: log Aircraft per Hour Worked

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
log Aircraft Demand	-0.027	0.281**	0.284**	0.248**	0.247	0.105	-0.091	0.141
	(0.022)	(0.130)	(0.114)	(0.110)	(0.159)	(0.108)	(0.192)	(0.297)
Demand × Capacity Util.	0.082***	0.236***	0.249***	0.187**	0.255***	0.371***	1.345***	0.535
	(0.025)	(0.087)	(0.083)	(0.076)	(0.083)	(0.078)	(0.398)	(0.510)
Observations	958	958	847	942	944	958	958	805
Adjusted R^2	0.708	0.492	0.531	0.610	0.524	0.460	0.506	0.530
First Stage F-stat		13.1	16.8	19	8.2	24.1	12.9	11.3

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Dependent Variable: TFP

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
log Aircraft Demand	-0.059***	0.272**	0.312**	0.270**	0.285*	0.092	-0.171	0.428
	(0.022)	(0.120)	(0.124)	(0.110)	(0.151)	(0.421)	(0.198)	(0.339)
Dem. × Capacity Util.	0.123***	0.229***	0.226***	0.171**	0.232***	0.302***	1.484***	0.209
	(0.025)	(0.082)	(0.084)	(0.078)	(0.083)	(0.242)	(0.406)	(0.583)
Observations	867	867	859	852	861	867	867	804
Adjusted R^2	0.720	0.519	0.464	0.597	0.503	0.578	0.549	0.367
First Stage F-stat		16.3	16.2	20.6	9.6	33.2	15.3	11.3

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: Regression results showing the response of labor productivity (top panel) and TFP (bottom panel) to a 1% increase in aircraft demand their interaction with a dummy indicating whether capital utilization was above median at the beginning of the war. The first row has gives the response of productivity in plants with below average capital utilization and the second row gives the added productivity response in plants with above median utilization. Coefficients are the β_{12}^{LBD} and β_{12}^{LBN} coefficients of local projections estimates of (6). Column 1 shows an OLS specification, as in Figure A.3 in the appendix. Column 2 uses (and the remaining columns use) IV, with aircraft demand predicted by the instrument described in Section 3. Column 3 controls for the growth of factors of production from time $t-1$ to $t+12$, as in Figure 8. Column 4 controls for (log) cumulative production, or “experience”. Column 5 controls for cumulative capital investment in equipment. Column 6 weights observations by each plant’s total production over the duration of the war. Column 7 interacts demand with capital utilization at the beginning of the war (a continuous measure), instead of above median capital utilization, so that the first row represents the projected effect of demand on productivity for a plant with zero utilization and the second row gives the marginal effect of an additional percentage point of capital utilization times 100. Column 8 interacts demand with a time varying measure of capital utilization (12 month lagged) instead of initial capital utilization. Anderson-Rubin p-stat < 0.01 in all specifications.

Table A3: Summary Statistics: Airframe Plants by Capacity Constraint Measures

	Capital Utilization		Hours/Worker		Wages		WMC	
	Low	High	Low	High	Low	High	2-4	1
$\Delta_{\%}$ Output per Worker	127%	104%	107%	114%	117%	103%	112%	108%
Firm Age (Months)	172	191	168	200*	178	190	183	184
Plant Age (Months)	65	137***	132	84**	110	108	92	129*
Hours per Pound	3.2	3.1	2.4	3.7	3.0	3.4	3.5	2.7
Airplanes Produced	38	77	67	60	77	54	56	72
Unit Cost (000's USD)	107	124	109	131	87	147	88	138
Wing Span (Meters)	21.8	19.7	17.5	23.5**	20.9	19.8	20.8	20.1
Public Plant Financing (mln USD)	15.0	14.5	10.3	18.7	16.9	11.9	14.7	14.7

Note: Summary statistics for airframe plants along sample splits reflecting different dimensions of capacity constraints. These are (1) capital utilization as measured by shift utilization, (2) weekly hours per worker, (3) county-level wages, and (4) War Manpower Commission local labor market classification (1 to 4, decreasing in labor shortages). "High" columns give averages for plants above median by the metric in question in January 1943. Averages are for January 1943, except for plant financing (cumulative to January 1945), hours per pound (January 1945), growth in aircraft per hour worked (log change from Jan 1943 to Jan 1945). Asterisks reflect statistical significance of the t-test of differences between the two categories: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Sources: AMPR War Production Board *War Manufacturing Facilities Authorized*, and the author.

Table A4: Correlation Between Measures of Aircraft Plants' Capacity Constraints

	Capital utilization	Hours per worker	Wages	Labor market priority
Capital utilization	1			
Hours per worker	0.32 *	1		
Wages	0.11	-0.02	1	
Labor market priority	0.29 *	-0.04	0.42***	1

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: The table gives correlations between various indicators of capacity constraints. The variables are capital (shift) utilization, hours per worker, wages in the local labor market (excluding aircraft plants), and a dummy equaling one if the Manpower Commission classified the labor markets as facing labor shortages. Sources: AMPR, War Production Board, War Manpower Commission.

Table A5: Correlates with Modification Center Employment

	(1)	(2)	(3)	(4)	(5)
Dependent Variable	Hours in plant	Productivity	Productivity	Productivity	Productivity
Mod. Ctr. Employment	0.912***		-0.018	0.033	-0.021
	(0.040)		(0.051)	(0.121)	(0.086)
Hours in Plant		-0.002		-0.047	
		(0.008)		(0.101)	
Mod. Ctr. $\times$					0.005
High initial capacity Util.					(0.104)
N	179	2550	153	153	153
adj. R^2	0.830	0.138	-0.035	-0.042	-0.044

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: Regressions of the growth in log hours worked in a production line (column 1) or the growth in log aircraft per hour worked (columns 2 to 5) against the growth of log employment at the corresponding modification center. All regressions include month and plant $\times$ model fixed effects. In multi-product plants, modification center employment allocated to production lines according to the relative growth in output. Results are robust to regressions at the plant level. Column (1) shows a strong correlation between hours worked at the plant and at the modification center. Columns (2) to (4) show little correlation between productivity growth and employment growth at the modification center, suggesting that productivity growth at the plant isn't due to additional work at the modification center. Sources: Hours and productivity at the production line from USAAF (1952) Vol. 1: Direct Man-Hours - Progress Curves, Table 2. Modification center employment from *Total Labor Requirements for the Aircraft Industry WL-8*, RG 179, Boxes 2471-5, NARA College Park.

B A Simple Model of Learning by Necessity (For Online Publication)

This appendix outlines a theory of "learning by necessity" that illustrates why plants might increase productivity in face of high demand when facing tight capacity constraints. The theory highlights that demand *relative* to plants' existing capacity affects the choice of innovation or technology adoption. This leads to an interaction between demand and capacity utilization. Plants adopt productivity-enhancing methods when their benefits justify their adoption costs. If operating at high capacity is costly (formally, if utilization costs are convex), cost reductions will be more beneficial when demand is high relative to existing capacity. New techniques are therefore adopted when demand is high relative to installed capacity.

The intuition of the model can be fully captured in a one-period model, with which I begin. A full calibrated model follows.

B.1 Static Model

A plant operates using a Cobb-Douglas production function of the form

$$Y_t \leq z\left(H_t L_t\right)^{\alpha}\left(U_t K_t\right)^{1-\alpha}, \tag{B.1}$$

where z is total factor productivity, L_t the number of workers, K_t the quantity of physical capital, H_t hours worked as a fraction of a full week and U_t the work week of capital (capital utilization). Both utilization variables range from zero to one. In the dynamic model, the plant can only adjust capital and labor over time and faces adjustment costs if it wishes to do so. The static model presented here takes these costs to the extreme and both these factors of production are in fixed, pre-determined, quantities. In contrast, the plant can choose labor and capital utilization, H_t and U_t, respectively, but faces convex costs to utilization. Concretely, monthly wages $w(H_t)$ are not only increasing, but also convex in hours worked. Overtime pay was prevalent (typically at a 50% premium) in the aircraft industry, so that the marginal cost of work hours was increasing in the length of the work week. Similarly, capital may depreciate more when highly-utilized, so that the cost of capital utilization is a convex function $\delta(K_t)$.

The production function and the plant's decision problem that follows are similar to those in Basu *et al.* (2006), with one twist. The plant begins with a traditional technology from which it derives total factor productivity $z = z^T$. (I use the term "technology" generically for all factors affecting TFP). After the plant receives demand $Y_t = \bar{Y}$ for its product, it chooses not only how intensively to utilize workers and capital, but also whether it wants to pay a cost A to adopt a new (modern) technology with TFP $z = z^M > z^T$. This simple discrete jump will be undertaken if the savings in utilization costs exceed the adoption cost A.

Given its chosen technology, the plant chooses utilization H_t and U_t so as to minimize utilization costs

$$\min_{H_t, U_t} w\left(H_t\right) L_t + \delta\left(U_t\right) K_t$$

subject to satisfying demand $\bar{Y}$

$$z\left(H_t L_t\right)^{\alpha}\left(U_t K_t\right)^{1-\alpha} \geq \bar{Y} \tag{B.2}$$

Optimal utilization equates the marginal cost of utilizing the two factors:

$$w'(H_t) H_t L_t = \delta'(U_t) U_t K_t. \tag{B.3}$$

Marginal costs of both forms of utilization increase in tandem and are both increasing in the term

$$\text{Demand/Capacity} = \frac{\bar{Y}}{z L_t^{\alpha} K_t^{1-\alpha}}. \tag{B.4}$$

This term scales demand by the plant's current (maximal) capacity. It follows directly from (B.2) that this ratio determines–and increases–utilization.

A surge in demand $\bar{Y}$ increases utilization and marginal costs and more so the lower is TFP z, because the demand is pressing against lower productive capacity, as in (B.4). This is illustrated Figure A.13a, which shows cost curves: utilization costs as a function of demand $\bar{Y}$. The two curves represent high and low values of TFP, corresponding to the modern and traditional technologies, respectively. Costs are convex by assumption and the gap between the two is increasing in demand, per (B.2) to (B.4). The figure shows that the cost savings due to technology adoption is increasing in demand. Technology is optimally adopted if the gap between the two curves is larger than the adoption cost A, so when demand is sufficiently high, all else equal.

But this is only part of the story. It isn't merely the absolute level of demand, but rather demand relative to the plant's capacity that determines where we are along the cost curves in the figure. Utilization is endogenous, but equations (B.2) and (B.4) indicate that it is a sufficient statistic in equilibrium for demand pressures relative to capacity. A plant operating at low levels of utilization will be on the flat portion of the cost curves in Figure A.13a, where an increase in demand $\bar{Y}$ will have little impact on costs and therefore on technology adoption. In contrast, a plant operating at high utilization will be further to the right along these curves, were an increase in demand has a larger impact on marginal costs and on the benefits of technology adoption. Here a demand shock is more likely to tip the scales towards the modern technology.

This is shown in Figure A.13b, which now shows the cost savings due to technology adoption (the gap between the curves in Panel A) as a function of utilization. Utilization is of course endogenous, but governed by initial capacity, as in (B.4). The gains to technology adoption are increasing and convex in utilization, so that technology adoption is more likely at high utilization rates, and more so in face of surging demand. This is the theoretical counterpart of the triple difference in differences specification of Section 4 and describes "learning by necessity" in a nutshell.

Basu *et al.* (2006) use a similar framework to show that *measured* TFP will increase when demand is high. This is because utilization increases with demand but is typically unobserved in the data, giving the semblance of higher output with the same means of production. The theory here suggests that not only measured, but *actual* TFP may increase with demand, now because high utilization induces firms to adopt productivity-enhancing measures. This is supported by the empirical results, where TFP adjusted for capital utilization increases in demand, and more so when utilization is high .

B.2 Dynamic Model

We now turn to the dynamic model. The length of a period t is one year. The production function remains as in (B.1). However, now plants can invest (or dis-invest) in new capital I_t and hire (or lay off) workers, with D_t denoting the net change in workers employed. Capital and labor evolve according to the following two constraints:

$$K_{t+1} \leq I_t + (1-d)\, K_t; \tag{B.5}$$

$$L_{t+1} \leq L_t + D_t; \tag{B.6}$$

where d is the capital depreciation rate. The plant rents capital K_t at an interest rate r_t, a rate that also serves as the plant's discount rate. In addition to the convex costs to capital and labor utilization, described above, there are also adjustment costs to investment $I_t \equiv K_t - K_{t-1}$ and hiring (or firing) $D_t \equiv H_t - H_{t-1}$. These costs are given by $K_t J\left(I_t/K_t\right)$ and $w_t L_t \Psi\left(D_t/L_t\right)$ respectively, where $J\left(.\right)$ and $\Psi\left(.\right)$ are both convex functions; and w_t are annual wages per worker.

Wages have two components. There are monthly fixed costs to employ a worker of W_t, and each worker is paid annual wages of $w\left(H_t\right)$ that are a function of annual hours. Hence $w_t = W_t + w\left(H_t\right)$. A linear $w\left(H_t\right)$ function would represent hourly wages, while a convex function would represent wages that are increasing in hours worked, e.g. overtime pay.

The plant faces a discrete choice at time zero between one of two technologies $z = z^M$ or $z = z^T$ (modern or traditional), with $z^M > z^T$. Using the traditional technology is free (or a sunk cost), but using the modern technology incurs an adoption cost A (which could incorporate the net present value of any recurring costs to the technology's use).

The model has perfect foresight. A model with uncertainty would yield qualitatively similar results, but may lead to a smaller probability of adopting the modern technology depending on the nature of the uncertainty (about the duration of the war, the magnitude of the shocks, demand in the post war period). As we will see, the war shock gives such large incentives to upgrade technology that it would overwhelm any such hesitations and is unlikely to change the qualitative predictions of the model. With this in mind, the plant's cost minimization problem is

$$\min_{D_t,L_{t+1},I_t,K_{t+1},H_t,U_t,z_t\in\{z^T,z^M\}} \sum_{t=0}^{\infty}\prod_{j=0}^{t-1}\left(\frac{1}{1+r_j}\right)\left[\begin{array}{c} W_tL_t+L_tw\left(H_t\right)+ \\ L_t\left[W_t+w\left(H_t\right)\right]\Psi\left(D_t/L_t\right)+ \\ K_t\delta\left(U_t\right)+K_tJ\left(I_t/K_t\right)+r_tK_t \end{array}\right]+AI(z=z^M)$$

s.t (B.1) and (B.5) (B.6). $I(.)$ is an indicator function that takes on the value of 1 if the modern technology is chosen and zero otherwise.

The first order conditions (on D_t, I_t, L_{t+1}, K_{t+1}, H_t, and U_t, respectively) are as follows:

$$\Psi'\left(D_t/L_t\right)=\frac{\lambda_t^L}{W_t+w_t\left(H_t\right)} \tag{B.7}$$

where $\lambda_t^L=\frac{\tilde{\lambda}_t^L}{B_t}$ and $\tilde{\lambda}_t^L$ is the Lagrange multiplier on (B.6) at time t and $B_t\equiv\prod_{j=0}^{t-1}\left(\frac{1}{1+r_j}\right)$.

$$J'\left(I_t/K_t\right)=\lambda_t^K, \tag{B.8}$$

with $\lambda_t^K=\frac{\tilde{\lambda}_t^K}{B_t}$ and $\tilde{\lambda}_t^K$ representing the Lagrange multiplier on (B.5).

$$\begin{aligned} & w_{t+1}\left[1+\Psi\left(D_{t+1}/L_{t+1}\right)-\frac{D_{t+1}}{L_{t+1}}\Psi\left(D_{t+1}/L_{t+1}\right)\right] \\ = \quad & \lambda_{t+1}^L-\left(1+r_t\right)\lambda_t^L+\alpha\frac{z\left(H_{t+1}L_{t+1}\right)^{\alpha}\left(U_{t+1}K_{t+1}\right)^{1-\alpha}}{L_{t+1}}\lambda_{t+1}, \end{aligned} \tag{B.9}$$

where λ_t is the Lagrange multiplier on (B.1).

$$\begin{aligned} & \delta\left(U_{t+1}\right)+J\left(I_{t+1}/K_{t+1}\right)-\frac{I_{t+1}}{K_{t+1}}J'\left(I_{t+1}/K_{t+1}\right)+r_{t+1} \\ = \quad & \left(1-d\right)\lambda_{t+1}^K-\left(1+r_t\right)\lambda_t^K+\left(1-\alpha\right)\frac{z\left(H_{t+1}L_{t+1}\right)^{\alpha}\left(U_{t+}K_{t+1}\right)^{1-\alpha}}{K_{t+1}}\lambda_{t+1} \end{aligned} \tag{B.10}$$

$$L_tw'\left(H_t\right)\left[1+\Psi\left(D_t/L_t\right)\right]=\alpha\frac{z\left(H_{t+1}L_{t+1}\right)^{\alpha}\left(U_{t+1}K_{t+1}\right)^{1-\alpha}}{H_{t+1}}\lambda_{t+1} \tag{B.11}$$

$$K_t \delta' (U_t) = (1-\alpha) \frac{z (H_{t+1} L_{t+1})^{\alpha} (U_{t+1} K_{t+1})^{1-\alpha}}{U_{t+1}} \lambda_{t+1} \tag{B.12}$$

The first order conditions above apply for any value of z and the plant chooses the modern technology if it leads to cost savings greater than A.

The first order conditions equate the marginal costs of capital and labor utilization and both of these to the marginal costs of capital and labor adjustment. The former two costs are static, while the latter have dynamic implications. An increase in demand in the distant future can be accommodated by gradual accumulation of factors of production, incurring only small marginal adjustment costs in each period along the way, and without necessitating large increases in utilization at any stage. In contrast, front loaded demand, or a large MIT-style demand shock, will require large factor adjustments and the plant will optimally increase utilization to limit adjustment costs. The plant will choose the modern technology if the net present value of these costs are high. Because costs are convex, they will be higher if unanticipated and concentrated in early years.

Functional Forms

We assume the following functional forms for adjustment costs. Adjustment costs for capital and hiring/firing take on standard quadratic forms:

$$J\left(\frac{I}{K}\right) = \frac{\varphi}{2}\left(\frac{I}{K} - d\right)^2.$$

$$\Psi\left(\frac{D}{L}\right) = \frac{\psi}{2}\left(\frac{D}{L}\right)^2.$$

Capital utilization costs take the form

$$\delta (U) = \delta_0 \frac{U}{1-U}, \tag{B.13}$$

which bounds utilization between zero and one in equilibrium. Overtime pay is the most direct reason for convex labor utilization costs:

$$w(H) = \bar{w} \left[H + \omega (H - FT) \Xi (H > FT) \right], \tag{B.14}$$

where ω is the overtime rate, FT is full-time weekly hours, and Ξ is an indicator function equal to one if hours exceed full time and zero otherwise. Because labor costs are piece-wise linear in hours, hours may be unbounded in equilibrium. I impose a limit of 80 hours per week.

Table A6: Calibration

Parameter		Value	Method	Target
d	Depreciation rate	0.08	external	Post-war estimates
r	Real interest rate	0.03	external	Post-war value
W	Fixed costs per worker	$= 0.25\bar{w}FT$	external	25% overhead per worker, typical estimates
$\bar{w}$	Hourly wage	0.658	internal	To match $\bar{H} = FT = 0.24$ to a 40-hour work week (out of 168 hours), full time
ω	overtime rate	0.5	external	Typical 50% overtime rates in aviation industry
δ_0	K Utilization cost param.	0.0967	internal	to match $\bar{U} = 0.36$
				1.5 8-hour shifts, 5 days a week, post war average
α	labor share	$\frac{2}{3}$	external	Typical value in the literature
ϕ	K adj. cost param.	1.2	internal	To match 1.2 log point decline in capital stock 1944-48
ψ	L adj. cost param.	0.975	internal	To match 1.65 log point decline in capital stock 1944-48

Calibration

The model will be simulated so that that it begins from a steady state calibrated to features of the pre-war aircraft industry, is then hit but a one-off, unanticipated shock matching the features of World War II, and then converges to a new steady state (with a higher level of TFP) that matches features of the post-war economy. The model is parametrized to match the post-war economy and initial conditions are then adjusted to shrink the industry to its pre-war levels.

I normalize the the stock of capital, labor and TFP to one, $z = \bar{K} = \bar{L} = 1$, in the post-war economy steady state. Most remaining parameters are calibrated externally. Parameters of the utilization cost functions can be calibrated to match post-war utilization rates exactly in steady state. Capital and labor adjustment costs are zero in steady state, but govern the rate of investment and hiring along a dynamic path. They are calibrated to match the rate of capital dis-accumulation labor force decline in the airframe industry following the war. Table A6 shows calibrated values and calibration targets. Steady state variables are denoted with bars. Aggregate data on the pre- and post-war airframe industry are from Kupinsky (1954) and Lee (1960).

Simulation

The plant in the model is confronted by a sequence of aircraft demands Y_t, matched to the actual production path during the war. For the average plant, this is set as follows. With $z = \bar{K} = \bar{L} = 1$ (normalized to 1) and hours worked and utilization set at the targets shown in Table A6, the post-war steady state level of production is $\bar{Y} = 0.274$, from (B.1). Demand Y_t in all other years is set relative to this index, and taken from the data. Specifically, this gives $Y_{1938} = 0.1$, which we treat as initial conditions and assume that the airframe industry had this level of production in the pre-war steady state. TFP in the average plant grew by 35% during the war (see Figure 2). Accordingly, we set TFP in the pre-war period to $z = 0.75$. Capital and labor utilization rates are the same in the pre-war and post-war steady states. This gives $K_{1938} = L_{1938} = 0.3$, 30% of their post-war value, which is also consistent with the data. In 1938, at its pre-war steady state, the plant is informed of the future demand it will face in all future periods. For simplicity we ignore the Korean War, and the plant expects to be at the 1944-48 levels of aircraft demand for the remainder of history.

Simulations compare a scenario when the plant chooses to invest in the modern technology, which increases its TFP to one, as in the post war steady state, to a scenario where it retains its pre-war level of TFP of $z^T = 0.75$. In the former case we assume for simplicity that the productivity gains come immediately, so that $z = 1$ throughout.

Figure A.14 shows how a plant facing the average demand facing World War II aircraft plants responds to this demand shock, absent any increase in TFP during the war. The demand shock is enormous, with production peaking at 25 *times* its pre-war levels. Although capital and labor adjustments are costly, the plant has no choice but to rapidly accumulate capital and hire workers, even knowing that it will have to dispose of the capital and lay off the workers after the war. Capital and labor grow more than 6-fold, compared to a roughly 3-fold increase in the data, partly because the simulation doesn't allow plants to increase TFP. This demonstrates the massive costs that would be incurred absent productivity-enhancing measures. As in the data, the simulated firm accumulates factors gradually, to economize on adjustment costs. It is therefore compelled to utilize capital and labor intensely early in the war, until the newly installed capital and hired labor comes online, at which point utilization can decline to normal levels again, as in Figure 3. Capital utilization gives a rough sense of the evolution of marginal costs over the simulation, because capital utilization costs are convex according to (B.13), and marginal costs are equalized across all margins.[26] Higher productivity z would lower these adjustment and utilization costs and might justify the fixed cost to technology adoption A.[27]

FigureA.15 repeats this exercise, but now for a plant with lower demand. Specifically, it scales the war shock down by 28% to match the the production of the plant at the 25% percentile. The lower demand implies that the plant needs to expand capital and employment "only" four-fold and can do so with lower utilization. Capital utilization peaks briefly at almost 60%. In comparison, the average plant in Figure A.14 had has such utilization rates throughout the war. Lower demand leads to a substantially lower net present value of costs, giving a smaller incentive to adopt the technology.

Figure A.16 now brings demand back up to that of the average plant and simulates the case of low capacity utilization. Utilization is endogenous and one needs to consider an exogenous

[26] Labor utilization costs are convex, but piece-wise linear, so that hours worked shoot up dramatically–more so than in the data. This may indicate that labor utilization costs are convex beyond the costs of overtime pay.

[27] The figure also shows very low utilization in the post-war period because demand has declined, but plants still have an overhang of capital and workers from the the war. This is consistent with the minor recession in the US economy in late 1945 and early 1946. In the model, as in the data, utilization rates return quickly to normal.

force driving utilization. In the data, high utilization plants were those whose demand was front-loaded, leading to high utilization early in the war. To replicate this in the simulation, I give the plant a 2-year "advance notice" of the demand. This is sufficient to match the initial capital utilization of the 25% percentile plant. The advanced notice allows the plant to ramp up capacity more gradually, economizing on adjustment costs. The plant utilizes capital less intensely and also saves on utilization costs. This plant will have lower costs and less of an incentive to adopt the modern technology.

Relating these simulations to the triple difference specification in Section 4, I conduct the following experiment. The model is simulated with low and high demand; with low and high utilization; and with or without adopting the modern technology, as described above ($2 \times 2 \times 2$ simulations in total). High and low demand are matched to the 75$^{\text{th}}$ and and 25$^{\text{th}}$ percentile plants representing demand that is 2.9 times higher and 28% lower than the average plant, respectively. High and low utilization are matched to the 75$^{\text{th}}$ and and 25$^{\text{th}}$ percentile plants in terms of utilization. I then calculate the cost savings arising from technology adoption in all four scenarios, that is the cost difference between the high and low TFP simulation in each case. This gives the plant's (maximal) willingness to pay to obtain a 35% TFP increase, as observed in the average plant during the war.

Figure A.17a shows the results. All bars give the net present value of the savings a plant obtains by adopting a technology that increases TFP by $\frac{1}{3}$. These are given as a fraction of the net present value of variable (capital rental, wages, adjustment, and utilization) costs, calculated over a 100-year horizon. The first two bars from the left are simulations of a high utilization plant; the next two bars are a low utilization plant. In each case, the bar on the left is the case of low demand and the bar on the right the case of high demand. The first feature that stands out is the sheer magnitude of the bars. Costs in the 6-year wartime period are so large that technology adoption could lower the plant's net present value of costs by as much as 70% *over the course of an entire century*. A second result is the big difference in costs, and therefore cost-savings due to technology adoption, depending on demand. A high demand plant is willing to pay more than twice as much as a low demand for the modern technology. Finally, willingness to pay is increasing in utilization.

Figure A.17b represents this same information a triple difference-in-differences. It gives the difference in savings (due to high rather than low TFP, as a percent of the net present value of costs) between the high- and low-demand scenarios, for simulations with high and low initial capital utilization. High demand incentives technology adoption, and more so at high rates of utilization, as in the empirical results of Section 4.

C Derivations for Section 3.1 (for online publication)

Cost savings in (1) can be rewritten as

$$C_{mp,t} = K_{mp}\delta\left(\frac{1}{K_{mp}}\left(\frac{Y_{mp,t}}{z^T}\right)^{\frac{1}{1-\alpha}}\right) - K_{mp}\delta\left(\frac{1}{K_{mp}}\left(\frac{Y_{mp,t}}{z^T}\right)^{\frac{1}{1-\alpha}}\left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}}\right),$$

and this can be linearized around $t-1$ values gives as

$$\Delta C_{mp,t} \cong K_{mp}U_{mp,t-1}\left[\delta'\left(U_{mp,t-1}\right) - \left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}}\delta'\left(U_{mp,t-1}\left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}}\right)\right]\Delta\log Y_{mp,t},$$

giving (2)

Further, (3) can be log-linearized around $t-1$ values as

$$\begin{aligned} E\Delta\log z_{mp,t} &= g\left(C_{mp,t}\right)\log\frac{z^M}{z^T}\Delta C_{mp,t} \\ &= \frac{1}{\bar{A}}\log\frac{z^M}{z^T}\Delta C_{mp,t}, \end{aligned}$$

giving (4).

Combining (2) and (4) gives

$$E\Delta\log z_{mp,t} \cong \Upsilon\left(U_{mp,t-1}\right)\Delta\log Y_{mp,t},$$

where

$$\Upsilon\left(U_{mp,t-1}\right) \equiv \frac{K_{mp}U_{mp,t-1}}{\bar{A}}\log\left(\frac{z^M}{z^T}\right)\left[\delta'\left(U_{mp,t-1}\right) - \left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}}\delta'\left(U_{mp,t-1}\left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}}\right)\right].$$

Log-linearizing $\Upsilon\left(U_{mp,t-1}\right)$ around the value in the average plant gives

$$\Upsilon\left(U_{mp,t-1}\right) \cong \Upsilon\left(\bar{U}_{t-1}\right) + \Upsilon'\left(\bar{U}_{t-1}\right)\left[U_{mp,t-1} - \bar{U}_{t-1}\right],$$

which motivates the estimating equation.

It is always the case that $\Upsilon\left(U_{t-1}\right) > 0$. This follows directly from the convexity of the cost function $\delta''(.) > 0$, which gives that

$$\delta'\left(\bar{U}_{t-1}\right) > \left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}}\delta'\left(\bar{U}_{t-1}\left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}}\right),$$

because $\frac{z^T}{z^M} > 0$.

Taking the derivative of the function with respect to U:

$$\begin{aligned}
\Upsilon'\left(\bar{U}_{t-1}\right) \quad \equiv \quad & \frac{K_i}{\bar{A}} \log\left(\frac{z^M}{z^T}\right)\left[\delta'\left(\bar{U}_{t-1}\right) - \left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}} \delta'\left(\bar{U}_{t-1}\left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}}\right)\right] \\
& + \frac{\bar{U}_{t-1}K_i}{\bar{A}} \log\left(\frac{z^M}{z^T}\right)\left[\delta''\left(\bar{U}_{t-1}\right) - \left(\frac{z^T}{z^M}\right)^{\frac{2}{1-\alpha}} \delta''\left(\bar{U}_{t-1}\left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}}\right)\right].
\end{aligned}$$

The term on the first line is always positive, again because $\delta''(.) > 0$. The second line is positive if $\delta'''(.) \geq 0$ because then we can unambiguously state that

$$\delta''\left(\bar{U}_{t-1}\right) - \left(\frac{z^T}{z^M}\right)^{\frac{2}{1-\alpha}} \delta''\left(\bar{U}_{t-1}\left(\frac{z^T}{z^M}\right)^{\frac{1}{1-\alpha}}\right) > 0.$$

However, this last inequality may even hold when $\delta'''(.) < 0$ because the $\left(\frac{z^T}{z^M}\right)^{\frac{2}{1-\alpha}}$ term decreases the negative term on the left hand side. Overall, we conclude that $\delta'''(.) \geq 0$ is a sufficient (but not necessary) condition for $\Upsilon'\left(\bar{U}_{t-1}\right) > 0$ for all $\bar{U}_{t-1}$.

Utilization is bounded between zero and one. The condition $\delta'''(.) \geq 0$ means that the cost of utilization is (weakly) increasingly convex. This condition will hold for cost functions that go to infinity when $U \to 1$ and ensure that it is bounded. For example, in the calibrated model in Appendix B we use $\delta(U) = \frac{U}{1-U}$, which satisfies $\delta'''(U) > 0$. A simple quadratic cost would have $\delta'''(.) = 0$ and would also satisfy this equation.

D External Validity

How specific are the results reported here to the peculiar circumstances of the Second world War? I now discuss several facets of the historical context that help evaluate the external validity of the paper's findings.

Aircraft Standardization

A major shift during the war was was the move from made-to-order aircraft to standardized airplanes and this was crucial to satisfy the growing demand for aircraft (Middleton 1945, Claussen (1951) p. 23, Klein 2013, p. 52). Standardization, however, makes the wartime airframe industry similar to modern civilian industries. Standardization is in itself standard. Product standardization pre-dated the war: Henry Ford famously reports instructing his sales-force in 1909 that "Any customer can have a car painted any color that he wants so long as it is black" (Crowther & Ford 1922). The auto industry froze standard designs for extended periods of time and its production line methods went hand in hand with product standardization (Mawdsley 2020, p.270). Mishina (1999) compares the wartime airframe industry with the "just in time" production methods that proliferated in post-war era. However, the aircraft industry may have been on the cusp of a transition to standardization and mass production and large wartime demand may have merely nudged the industry into its next developmental stage. It is reassuring that learning curves appear no steeper in this industry than in others (see below). Nevertheless, further research is needed to adjudicate whether "learning by necessity" is particularly strong in an industry at this developmental stage.

Price Controls

The aircraft industry was exempt from the the Emergency Price Control act of 1942, an exemption that covered everything from "the raw material up to the finished product" (Smith 1991, p. 404). Static price caps would have had little effect given that aircraft prices (for a given model) dropped precipitously and across the board between 1942 to 1945.

Most aircraft were purchased through cost-plus-fixed-fee contracts. The government would typically offer a contract for a fixed quantity of an aircraft model, commit to toe the bill for the plant's variable costs, and to pay a pre-determined payment per aircraft delivered. This contrasts with the fixed-price contracts, prevalent in modern procurement. The former provides weaker incentives for cost-reductions, because these are passed through to the government, rather than accruing as profits. An excess profit tax of 90% was imposed on profits exceeding 4% of costs, and these might seem like a back-door price control. In fact, caps on markups reduced producers' incentives to lower costs further.

The modern literature on optimal procurement sheds further light on the perverse incentives due to cost-plus-fixed-fee contracts and markup caps. The literature focuses on asymmetric information between buyers and contractors, either regarding the contractor's private information about production costs, or about its unobserved effort to reduce costs. Regarding unobserved effort, Bajari & Tadelis (2001) show that cost-plus-fixed-fee contracts provide lower incentives to reduce costs than fixed-fee contracts. The logic is that in the latter, the contractor captures all surplus due to cost reductions for a given project (number of aircraft, in this paper's context). In contrast, when offering a cost-plus-fixed-fee contract, cost reductions are fully captured by the buyer. (There are some additional subtleties when costs are uncertain to both buyer and contractor, or when the buyer and contractor interact repeatedly, as in Laffont & Tirole (1988), but the general point still remains.) This implies that the contracts used during World War II provide weaker incentives to reduce costs and increase productivity than do the fixed-price contracts that are the default in modern procurement.[28]. McCall (1970) adds that cost-plus-fixed-fee contracts may lead to adverse selection because high-cost firms have the incentive to submit lower cost estimates when bidding for contracts, knowing that their costs will be covered either way.

Later in the war, whenever the profit cap was binding, the resulting contract was equivalent to a cost-plus-*percentage*-of-cost contract, where the government reimbursed 104% of production costs per aircraft delivered. This contract structure dis-incentivized cost reductions further. Relative to cost-plus-fixed-fee, any cost reductions were not only passed on to the government, but also reduced the contractor's profits in dollar terms. The literature on optimal procurement contracts is essentially unanimous that this contract structure provides highly perverse incentives, and this contracting structure has long been abandoned. Writing about cost-plus-percentage-of-cost (CPPC) contracts during World War I, Reda (1968) notes that "CPPC contracts, whatever their merits, quite naturally encouraged wasteful and costly performance... suspicions grew that contractors were not being merely indifferent to costs, but, indeed, were actively seeking ways to increase them." Smith (1991) , p. 276, discusses how the excess profit tax dis-incentivized cost reductions during the Second World War.

There is a separate question of whether demand induced by government procurement is informative about demand surges more generally. Firms with market power may have lower incentives to reduce costs when facing high market demand because increased production partly cannibalizes existing profits. In contrast, the government, a monopsonistic buyer of military materiel, has greater power to dictate quantities produced, and negotiate contracts that incentivize productive investments.

[28]See https://www.acquisition.gov/far/part-16

The Office of Price Administration attempted freeze wages at March 1942 levels, but frequent pay raises were negotiated between the OPA, management and labor. Wages in aircraft-manufacturing counties increased by 20% from 1942 to 1945.[29] Wage controls led to some labor shortages (Fairchild & Grossman 1959 pp. 135-36), but wages were strongly correlated with labor shortages, (Table A4 in the appendix), indicating that the price mechanism was operating at least to some extent. I exploited variation in labor shortages as markers of labor pressures at the plant level in Section 4.2, but results were robust and even stronger when considering variation in wages instead (Figure A.9 in the appendix), so results appear to hold whether prices or quantities are used to measure labor market pressures.

Patriotism

While patriotism may have affected productivity growth during the war, it is easy to understate the persistence of mundane incentives. Absence rates were high, averaging 6% in aircraft plants, and peaking at nearly 10% at the median plant at the end of 1943 (see Figure A.12 in the appendix). More than a quarter of Boeing's workforce were absent on the day after Christmas, 1943; the day following payday was also a common day of absence (Klein 2013 pp. 542-43). Klein (2013) claims that absenteeism was high due workers' strong bargaining power, with this being a "sellers market".

Quit rates were also high, averaging 4% per month. These were as high as 50% per month at Ford's celebrated Willow Run plant (Klein 2013, p.534). Eiler (1998) (p. 379) calculates that the turnover rate for US industry was as a high 100% per year. He quotes Hap Arnold, Commanding General of the Army Air Force, lamenting that patriotism was insufficient to avoid high quit rates. War Production Board chief Bill Knudsen also complained that "both managers and workers were unwilling to work flat-out–in fact, people were feeling more and more free to take time off" (Herman 2012, p. 414).

At the war's onset, labor leaders pledged to avoid strikes and walkouts (Atleson 1998, p. 3). However, Brecher (1997) documents that this cohesion didn't last and that unofficial strikes increased from 1942 to 1944, the latter having more strikes than in any year in US history (p. 240). According to Senate documents, 2,116,000 workers took to the picket line that year across 4,956 strikes (Swafford 1947).

In summary, while patriotism may have motivated workers to some extent, it doesn't appear that the workforce abandoned self-interest.

[29]Source: "Summary of WBP-732 for Large Metal Products Manufacturing Plants," Record Group 221, Box 986, NARA College Park.

Aircraft Quality

Aircraft model fixed effects reflect narrowly defined aircraft, alternating with each design change. For example, Bell Buffalo's P63 models A and C are coded separately from models E and F and from G and I. Any changes in aircraft design would be captured by the model fixed effects. It is possible that aircraft quality declined *within* model, but there is no quality control record for World War II aircraft, to my knowledge.

There were a handful of sensational cases of plants attempting to cut corners to meet production targets. In January 1943, the Truman committee investigated and confirmed allegations that a subsidiary of Curtiss-Wright corporation had delivered defective engines.[30] However, by its March 1944 report, the committee informed that at Curtiss-Wright "improvements have been substantial, that the engines are being properly inspected and produced in great quantity." The committee also investigated complaints at the Curtiss-Wright Buffalo plant producing C-46 transport aircraft, but it was unable to confirm cases of defective planes.[31] The Truman Committee's reports mention no quality control problems in other airframe plants. Rae (1968) (p. 142) concludes in his history of the US aircraft industry that the "risk of exaggerating quantity at the expense of quality... did not in fact materialize in any serious proportions." Riddle (1964), p. 137, also concludes that cases of this sort were rare.

Data from modification centers provide further suggestive evidence that measured productivity didn't come at the expense of quality. Modification centers adapted the standardized aircraft to specific operational purposes, but also checked for and repaired production flaws. If productivity was associated with diminished quality, we'd expect to see increases in modification center employment as productivity grew. Table A5 in the appendix investigates this for the few modification centers that can be uniquely associated with a single plant. There is a nearly one to one relationship between modification center employment and hours worked in the plant, even controlling for two-way fixed effects, suggesting that the former didn't substitute for shirking in the latter. Further, there is essentially a zero correlation between growth in labor productivity and in modification center employment.

Was Aircraft Special?

Although studies of other industries use different methodologies, they report reassuringly similar learning effects. Thompson's OLS estimates of the Liberty Ship learning curve (0.26 in Table 2 and

[30] "Additional Report of the Special Committee Investigating the National Defense Program, Report 10, Part 10, 78th Congress, 1st session, pp. 107-111.

[31] "Additional Report of the Special Committee Investigating the National Defense Program, Report 10, Part 16, 78th Congress, 2nd session, pp. 107-111; United States Senate "Hearings before a Special Committee Investigating the National Defense Program," S. Res. 55, 79th Congress, 1st session, July 10-13, 1945.

0.21 in Table 3, last columns in both) are of similar magnitude to that found in here. Lafond *et al.* (2022) estimate an OLS regression of the learning (cost) curve, pooling the aircraft, shipbuilding, and trucking industries during the war and obtain an almost identical coefficient (-0.32 in their Table 3). While the aircraft industry was poised for mass production, the shipping and trucking industries were more mature. Of course, the existing literature doesn't investigate "learning by necessity', so it is difficult to adjudicate whether this phenomenon depends on the industry's developmental stage.

E Case Studies (for online publication)

This appendix gives narratives of the changes that occurred at a few plants in response to demand pressures.

Boeing, Seattle

This history draws on Mishina (1999), who gives a case study of the learning curve in B-17 production at the Boeing plant in Seattle. His main conclusion is that the learning process was one of "learning by stretching," a notion that anticipates and inspired the notion of "learning by necessity" of this paper. Mishina's "learning by stretching" refers to months in which a plant receives a previously unprecedented record of orders. Conceptually, this puts pressure on the plant's limited capacity, as in "learning by nececessity" but he had to rely on this indirect measure of production peaks, absent data on capital utilization.

Labor productivity in B-17 production in this plant increased by 240% from Pearl Harbor to the end of the war. The capital to labor ratio increased by 60% and production scale remained roughly constant over this period, so that TFP increased substantially with any reasonable production function parameterization. This was one of the highest capital utilization plants, with utilization peaking at more than 60% in early 1942; workers worked 50 hour average work weeks at that time.

Mishina (1999) (pp. 162-3) highlights how high bomber demand a plant with already high utilization motivated the need for technological change:

> After February 1942, turnover either outpaced or matched hiring, and the number of direct workers consequently fluctuated around 17,000 for the rest of the B-17 program. In fact, the chronic labor shortage was so severe that Boeing set up feeder plants in the summer of 1943 to tap into labor supplies outside the immediate Seattle area... It did not take long to exhaust this source, however: the subcontracting ratio already reached 28 percent with the B-17E and never exceeded 33 percent thereafter.

However, he rejects conventional human capital explanations for "learning" (p. 163). In fact,

> Unlike the plant and equipment, the workforce underwent significant qualitative changes during the mass-production phase and its skill deteriorated considerably. The early variants of the B-17 were built by a group of skilled craftsmen who had learned the ins and outs of airframe production through trial and error. With the outbreak of the war, these men either enlisted or were promoted to supervisory positions, and Boeing had to tap into entirely new labor pools to staff [Seattle] Plant No.2... Moreover, whatever

> labor Boeing was able to employ did not stay with the company long enough to acquire new craft skills. For example, Boeing started hiring female workers for the first time in its history to cope with the chronic labor shortage... [these workers] had a factory job only for a year or two when Plant No.2 recorded its best performance.

Instead, Mishina (1999) (p. 165) points to the same processes of specialization and interchangeability of parts that Adam Smith observed two centuries earlier, and more modern notions of "just in time" (JIT) production: "A primary cause of the rising velocity at Plant No.2 was the tighter implementation of JIT production." Concretely:

> The shop floor's crowded condition caused wastefulness, confusion, and inefficiency with increase in orders. Their solution was to streamline the process so that the right number of fabricated parts could reach the right place at the right time and the entire flow could be in a direct line to the last operation. They abolished the central finished-parts stockroom and made sure that the small stock bins carried only eight to ten days' supplies. This story amounts to a prefiguration of today's just-in-time (JIT) production... Plant No.2 divided the subassembly area into an ever larger number of smaller sections. As a result, the direct workers could work on a larger number of airframe segments of a given airplane at any given moment in the factory without interfering with one another.

Officials at Boeing credited this "production density" system for its production achievements.[32] This flexible technique was the brainchild of executive vice-president H. Oliver West. Improvement of procedures to limit human error was another administrative improvement:

> [M]uch had to do with procedures and simple devices. Plant No.2 reduced these opportunities for human errors with production illustrations, templates, and revisions of tooling development procedures.

In summary, the Boeing Seattle plant relied on new managerial and organizational procedures to increase productivity in face of high demand against constrained capacity.

Douglas, Santa Monica

This history draws on contemporary Wall Street Journal reporting. This plant also illustrates the importance of managerial innovations to facilitate mass production. It's largest product by volume was the A-20 light bomber. Although this was a relatively mature product, the plant's labor

[32] "There's No Single Long Assembly Line in Boeingâs Production of Fortresses," *Wall Street Journal*, 28 September 1942.

productivity more than doubled from 1942 to 1945. The plant's scale was roughly constant, but it's capital to labor ratio declined and then recovered, over the course of the war. The plant operated at a 67% rate of capital utilization in 1943–exceedingly high for the time, but brought this down to 46% by the end of the war. Worker's weekly hours were more stable at around 45 throughout the war.

Reporters detailed how Douglas Aircraft increased its output in its Santa Monica plant by implementing a new system of drawing blueprints that made them easier to interpret without high levels of prior knowledge. The firm developed the "cutaway three dimensional" drawing, and this new type of drawing was adopted across the industry. Douglas vice-president Arthur E. Raymond claimed that the new drawings were so effective that they had "greatly sped the planning and the operation of assembly lines for the mass production of fighting aircraft."[33]

North American, Kansas City

This history draws on Macias (2005). The North American plant in Kansas City was built in 1941 to produce B-25 bombers. It's labor productivity grew almost threefold from the beginning of 1943 to mid-1945. The capital to labor ratio nearly doubled, but scale remained roughly constant. From 1943 to 1945, the plant operated reduced its capital utilization rate from 55% to 47% and weekly hours per worker from 50 to 45.

The plant saw a big increase in productivity in 1943, after Harold R. Raynor was appointed as the new plant manager. Raynor introduced new sub-assembly methods to B-25 production. "Engineers applied sub-assemblies, an assembled unit designed to be incorporated with other units, to the [B-25] Mitchell. Five sections - front, center, rear fuselage, wings, and empennage - were broken down into assemblies, split into sub-assemblies, and further divided into component parts" (Macias 2005 p. 257).

New management also focused on labor relations. In the first month of 1943 the plant had an average rate of absenteeism of 8.2%. North American established several incentives to address this, including rewarding workers with the best attendance records with free war bonds, awarding cash prizes to workers who came up with the best patriotic slogans emphasizing the importance of staying on the job, and changing the work schedule to allow workers more time off. The plant moved from running two ten-hour shifts, six days per week to two ten-hour shifts, five days a week plus a rota-based weekday off. Absenteeism decreased to an average of 3.2% by 1945.

[33] "Douglas Speeds Output with New Type of Drawings for Mechanics," *Wall Street Journal*, 22 September 1941.

Bell, Marietta

This history draws on Combes (2001); "Appendix No. 1, Statement by Lawrence D. Bell, President, Bell Aircraft Corporation", October 10, 1945, before the Sub-Committee on Aircraft and Light Metals of the Special Committee Investigating the National Defense Program, United States Senate," Airforce Historical Research Agency, REEL A2169; and "Outline History of B-29 Program at Bell Bomber Plant," 22 Dec. 1941 to 31 Dec. 1943, REEL A1513. The Bell plant in Marietta, Georgia was founded to produce B-29 bombers. Labor productivity increased by a factor of 7 from the beginning of large-scale production in early 1944 to the end of the war. TFP increased by at least as much based on reasonable calibrations: the capital to ratio more than halved over this period, even as production scale doubled. Workers had 47 workweeks on average as production began, but this came down to 40 hours by mid 1944. Capital utilization was 48% in early 1944, slightly above the national average at that time.

The Marietta plant saw many of the improvements in production techniques documented elsewhere, but Combes (2001) emphasizes the role of labor conditions in the plant's success at exceeding its expected throughput. The company built hundreds of houses adjacent to the plant, constructed of car parks to facilitate commuting, and a traffic management system to make shift changes run smoothly. The firm also transported workers by bus from as far away as sixty miles. Recognizing the particular need of new women workers, Bell ran day care centers and held family days. The plant operated sports programs, rewarded worker suggestions with cash awards, opened a cafeteria to feed workers, gave workers a Christmas bonus in December 1944, and a day off for Christmas shopping as a reward for obtaining the plantâs monthly production target.

General Histories

I turn now to general histories of the period, that give an account of the importance of new production techniques, outsourcing, and labor relations in enhancing productivity.

Before 1940, aircraft production was a handicraft process. Aircraft were custom made to the client's (mostly the US- or a foreign-government's) specifications, limiting the pace of production. Visiting the Consolidated Aircraft factory in San Diego–a plant that later produced the greatest number of planes–George E. Sorensen, a Ford Motor Company executive, observed: "Here was a custom made plane, put together as a tailor would cut and fit a suit of clothes," (Sorensen & Williamson 1957). Mass production methods had already been in use in the automotive industry for decades, but management in the aviation industry insisted that these methods couldn't be adopted in the more complex process of airframe assembly, where each aircraft required hundreds of thousands of separate parts. As Klein (2013) puts it: "Nobody had yet found a way to bring mass-production techniques to airplane building, and prospects for doing so did not look promising" (p. 71).

The war modernized this industry. Aided in part by advice (and management hired) from the automotive industry, the aircraft industry adopted new production methods over the course of the war. Klein (2013) describes the innovation thus: "Mass production of anything consisted of a few well-defined principles. The first step was to break the product down into as many interchangeable parts as possible. Those parts could then be manufactured in quantity and fitted together on an assembly line where the machines were arranged in proper order" (p.67). This was both driven and enabled by the surge in demand for their products: "The rush of orders finally compelled many [aircraft] companies to rethink how they made their product" (Klein 2013). Craven & Cate (1955) concur that the industry "remained a handwork industry until the enormous demands of 1940-41 forced a conversion to mass-production methods." They contrast this to the the pre-war period, when "business [orders from the government] was too erratic to encourage plant expansion or the adoption of elaborate production-line techniques." In a post-war study of production problems in wartime aircraft manufacturing, Lilley *et al.* (1955) write: "In peacetime, the aircraft industry had had no opportunity to acquire familiarity with line production techniques; these techniques were not needed to meet peacetime production demands and were not used because of their high cost at peacetime volumes of output" (p. 2).

Line methods required new equipment but not all technological progress was embedded in capital and much of the progress was organizational.[34] Here is how Lilley *et al.* (1955) (p. 40-41) describe the transition to line production methods:

> The most dramatic evidence of line production in 1944 was the arrangement of equipment in both airframe and engine plants so that a progressive sequence of operations could be carried out. This arrangement of equipment constituted the fist element needed to achieve quantity production. Channels were established so that production could flow without the back-tracking so characteristic of job-shop work....
>
> Controlled flow was the second important element needed to achieve the peak production of 1944. Steady flow along the final assembly lines required careful production control in the assembly, subassembly, and fabricating departments. Scheduling assumed new prominence. In order to supply assembly lines with the thousands of parts entering into aircraft production, and enormous amount of detailed clerical work was required...
>
> The third essential element in the peak production year of 1944 was the careful bal-

[34]Indeed, they were often associated with hiring new middle management from the automotive industries. This resonates with the Acemoglu *et al.*'s (2022) finding that hiring innovative managers is associated with radical innovation in modern data.

> ancing of operations in each production line... [T]he various feeder and final assembly lines were so geared together that each production line turned out the right number of components to maintain balance with the others.

Outsourcing annother factor to which contemporary reports attributed large productivity gains. Aircraft plants of the 1930s assembled the entire aircraft in house. However, with the introduction of mass production techniques, with interchangeable parts produced with narrow tolerances, it became possible to farm out parts of the production process to feeder plants.

These plants assembled specific parts of the aircraft–wingtips, for example–that were then transported to the airframe assembly plant, which integrated these parts in to the final assembly. Taylor & Wright (1947) (p. 75) describe this managerial practice, new to the airframe industry, writing:

> One ingenious form of expansion was the multiplicity of small feeder plants nurtured by the major companies in small suburban or rural communities, miles away from the congested central plants... Trucks brought fabricated parts from the main factories, and returned with the completed assemblies. Tooling made the pieces fit, no matter where they originated.

Craven & Cate (1955) (p. 25) continue: "The prime contractors had not used before 1939 the system of purchasing parts and sub-assemblies, so common among other industries, and in general they had little liking for it... This system allowed the use of a pool of unskilled labor... but it put a heavier burden on management and proved more difficult to schedule accurately than had previous methods." They add that this greater managerial burden was a cost not worth bearing until the scale of wartime demand made it viable: "It was not until 1940 that the volume of production required reached a point which seemed to justify putting official pressure on the industry to overcome its reluctance," they write (p. 546), indicating that in some cases it was War Production Board officials (often from the automotive industry) that nudged management in aircraft firms towards more outsourcing. A memo from the War Production Board to the National War Aircraft Council (a private-sector consortium of aircraft manufactures) urges greater reliance on outsourcing: "Most of the aircraft plants on the West Coast have recently developed feeder shops, employing 250 to 500 people... Turnover and absenteeism in these shops are at a minimum. We would suggest a further probing into the possibilities of sub-contracting a greater proportion of work."[35]

[35] Irving J. Brown and Roy L. Reuther (Aircraft Labor Office, War Production Board) to Clinton S. Golden and Joseph D. Keenen (War Aircraft Council), August 25, 1943. *Box 7, Archives of the National Aircraft War Production Council, Truman Library.*

As the war progressed, outsourcing to more distant feeder plants was used to overcome labor shortages in the tight labor markets of many aircraft plants: "The dispersal of subcontracts outside the critical area [of tight labor markets] was encouraged, with the result that in September the Boeing Company placed subcontracts for approximately 40 percent of its work and made plans to let out subcontracts for an additional 20 percent." (Fairchild & Grossman 1959, p. 132). FigureA.12b in the appendix shows the increasing reliance on sub-contracting during the war. It shows the share of worker-hours in the production of each aircraft that was conducted in feeder plants, in the median aircraft plant. This increased dramatically from 10% to 30%, beginning immediately with the demand surge following the attack on Pearl Harbor.

Finally, labor relations have also been emphasized as a factor affecting productivity. Strain on workers and worker dis-satisfaction are certainly plausible drags on productivity in the context of a high pressure economy with workers working 50 to 60 hours a week at a quarter of all plants in 1942.

Histories of the war economy emphasize the labor problem in this high-pressure economy. Klein (2013) writes:

> Absenteeism remained a serious problem despite dogged efforts to curb it. Fortune called it "The New National Malady." The aircraft industry seemed especially prone to it. On the day after Christmas [1943], 26 percent of all Boeing employees failed to show up for work, as did 11,000 workers at Douglas. The following month the Bureau of Labor Statistics estimated absenteeism for all industries at about 7 percent, many times the normal rate in peacetime.

Taylor & Wright (1947) describe the problem of absenteeism:

> To maintain delivery schedules, companies were forced to hire more workers than were needed, knowing that a percentage of them would be absent every day. But a time came when this "safety margin" of surplus workers could no longer be recruited. The factories had to reduce absenteeism or reduce the output of planes.

A report written by Douglas Aircraft management writes of the costs of turnover:[36]

> Mass labor turnover constitutes the industry's most serious manpower problem. The reduction of this turnover would relieve the pressure on present and future manpower requirements. Another advantage would be the greater efficiency that results from employees who remain on the job because the cumulative experience of these trained workers would not be lost by the individual plants.

[36] *Experience Incentives*: Undated report by Douglas Aircraft, prepared for the National War Production Council, *Box 8, Archives of the National Aircraft War Production Council, Truman Library*.

Wages were only one of many tools used to retain workers and ensure they show up:

> Many and ingenious were the devices used to cope with the problem. Factories sent telegrams to the homes of absentees, inquiring after their welfare and telling them how they were needed in the war. Others sent visiting nurses to make first hand check-ups... Surveys searched for the causes of absenteeism... Working conditions were improved... Transfers to new jobs were arranged when work was uncongenial or unsuitable... Safety engineers fought to cut down absences caused by accidents... Ryan Aeronautical in San Diego reduced absenteeism by twenty-four percent by publishing [charts] in the company magazine and in daily papers... revealing the peaks and lows of daily attendance... Convair [initiated] a sweepstakes for employees with perfect attendance records, with prizes totalling $10,000 in War Bonds every month. (Taylor & Wright 1947, p. 137)