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LEARNING BY NECESSITY: GOVERNMENT DEMAND, CAPACITY CONSTRAINTS, AND PRODUCTIVITY GROWTH

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January 9, 2023

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 measured 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 data from archival sources on US World War II aircraft production. Shifts in military strategy 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 cannot because demand has no effect on firms' productive capacity. An alternative view posits that firms can and do respond to demand shocks through increased productivity 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 paper revisits this canonical setting to investigate how government purchases affected productivity and whether plants' capacity constraints played a role in inducing productivity growth. The main finding is that plants took active measures to increase total factor productivity in face of surging demand. Importantly, demand-induced productivity growth is particularly prominent in plants already utilizing capital and labor at high rates. This suggests that plants find ways to increase productivity when demand pushes them to the limits of their production capacity. I refer to this phenomenon as "learning by necessity".

A large body of work has studied "learning by doing" (LBD): a term that encompasses the many ways plants may become more productive with experience, including in the context of World War II. This work has been extremely influential and stimulated a literature on learning by doing and endogenous growth. However, existing work has mostly skirted the identification challenge arising because plant productivity was certainly a consideration in allocating government purchases. I show that this is not merely a theoretical possibility but that traditional learning-by-doing regressions show substantial pre-trends and clear indications of reverse causation.[1]

In this paper, I use archival data sources on US aircraft production during World War II to shed new light on this question. Some of the sources are newly digitized and haven't been used since the war. I propose an instrumental variables strategy to address the identification challenge. 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. Procurement was indeed 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, the historical narrative outlined in Section 3 strongly suggests that 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 military strategy and battlefield circumstances, not production efficiency in any particular plant. Instrumenting the monthly production of each individual production line with national production of all other plants producing the same broad aircraft type gives variation in demand that plausibly

[1] Scott-Kemmis & Bell (2010) have also pointed to endogeneity problems in learning by doing estimates.

comes from strategic military needs rather than other factors driving an individual plants' productivity. I find that a quantity-based, and capital-utilization adjusted, measure of Total Factor Productivity (TFPQ) increases by one third of a percent for each additional percent of aircraft demand in the average plant.

The paper also documents a new finding: Demand spurs greater productivity growth in plants operating at higher rates of capacity utilization. In a triple difference-in-differences Local Projections Instrumental Variables (LPIV) framework, I show that plants with higher capacity utilization (measured at the beginning of the war) see 60% to 100% higher productivity growth in the year following a one percent demand shock. I measure capacity constraints using several separate, and imperfectly correlated, indicators: capital utilization based on detailed shift-utilization data; labor utilization (weekly hours per worker); high-wage labor markets; and the War Manpower Commission's (WMC) classification of labor markets by labor shortages.[2]

Plants took several active measures to increase productivity and satisfy rising demand. First, production methods in the aircraft industry changed dramatically over the war years. The most prominent improvement was the move from job-shop production methods (custom and nearly handmade production) to production line methods (standardized products, interchangeable parts, with smaller tolerances). Using newly collected data from historical news sources and firms' annual reports, I present suggestive evidence that high-demand plants were more likely to adopt new production methods, but only if they were also "high pressure" plants, operating at high utilization.[3] Second, the airframe industry moved from mostly in-house production to greater reliance on outsourcing and subcontracting. I find that plants operating at high utilization rates outsource 10% of their production hours to feeder plants in the six months following a shock to government demand, but those operating at lower utilization rates do not outsource more in respond to demand. Third, management made a concerted effort to improve working conditions and worker morale, thus reducing absenteeism and turnover. I use newly archived data on absenteeism and turnover to show that while plants with lower labor utilization (lower hours per worker) saw large losses of work hours due to absenteeism (roughly 6% in the 6 months following a 1% demand shock), absenteeism rose by less in plants with higher labor utilization. A similar result holds for quit rates. These findings are consistent with a historical literature detailing active measures taken by management to retain workers when facing high demand relative to their productive capacity. Fi-

[2] Initially capacity-constrained plants were on average older, but I show that the results are driven by heterogeneity in capacity constraints rather than in this confounding factor. Constrained plants appear similar to less-constrained plants on other dimensions. These were plants that were known entities earlier in the war and whose demand was therefore front-loaded, leaving them little advanced notice to build up their capacity.

[3] These findings are consistent with Mishina's (1999) case study of B-17 bomber assembly in Boeing's Seattle plants. He documents that "learning" was far more than a passive accumulation of production experience. It also went beyond capital-embedded technological improvements and involved changes in managerial practices and production systems, including the move to interchangeable parts and changes to the layout of the factory floor. He states anecdotally that these innovations were undertaken because of plants' limited capacity to meet the demand pressures they faced.

nally, I show that plants with large accumulated production during the war patented more in the decade following the war, but only if they were high utilization plants.

Why do firms learn by necessity? The answer is implicit in theories of endogenous growth. Firms facing convex costs to utilization find it disproportionately costly to meet higher demand for their products when operating at high utilization.[4] They therefore have more to gain from bearing the costs of innovation, technology adoption, and changes in managerial practices that would lead to productivity growth.[5] Similar mechanisms are found in the literature on induced innovation, but the connection with capacity utilization hasn't been studied previously.[6] I outline a simple model that makes the connection between theories of endogenous growth and capacity utilization in Appendix B.[7]

There is a voluminous academic literature studying the effects of government purchases on the economy, including research that uses military spending to identify government spending shocks (Barro 1979, Ramey & Shapiro 1998, Barro & Redlick 2011, Ramey 2011b, Nakamura & Steinsson 2014; Ramey 2011a, 2016, and 2019, and Chodorow-Reich 2019 for reviews). Unlike much of the extant literature, this article doesn't focus on the aggregate effects of public expenditures (the "fiscal multiplier") on GDP, private consumption or unemployment, but rather on the effects of fiscal policy on productivity and its dependence on capacity utilization. I provide detailed plant-level evidence on a specific transmission mechanism of government purchases and identify shocks to government purchases at the production line level. Antolin-Diaz & Surico (2022) show that the effects of aggregate US military spending are long-lived and stimulates innovation and private investment, consistent with the mechanisms studied here. Brunet (2021) uses World War II procurement data to study the effects of government spending on output and employment using state-level variation. Interestingly, the paper reports far larger effects of government procurement on GDP than on employment, consistent with the productivity gains I find in the aircraft industry. Auerbach *et al.* (2019) study the effects of modern military procurement on regional output, but don't focus on productivity.[8]

[4]See Boehm & Pandalai-Nayar (2022) for evidence of convex cost curves.

[5]The possibility that demand may affect productivity has been a topic of theoretical interest in Benigno & Fornaro (2018), Moran & Queralto (2018), Anzoategui *et al.* (2019), and Jordà *et al.* (2020), but the literature doesn't draw a connection to capacity utilization. Models with lock-in effects to older vintages of technology or path dependence, as in Arthur (1989), would also lead to non-linearity in firms' response to demand in their choice of technology.

[6]See Romer (1987) for a review, Newell *et al.* (1999) and Popp (2002) on induced innovation and energy efficiency. Hickman (1957) was an early contribution to this literature and linked capacity utilization to incentives for capital investment, known at the time as "the acceleration princple".

[7]The importance of market size on productivity has also been emphasized in the literature on international trade and innovation (Acemoglu & Linn 2004; Finkelstein 2004 De Loecker 2007, 2011; Atkin *et al.* 2017 Melitz & Redding 2021), but these focus on the long-run, as opposed to business cycle frequency and don't speak to importance of capacity utilization. Further, the mechanism is typically through the selection of more productive firms as the market expands, rather than productivity gains within firms due to the larger market scale.

[8]Fishback & Cullen (2013) use regional data to study the longer term impact of World War II public spending on economic activity and find limited long-run impact. Rhode (2000) studies the effects of wartime spending on the Cal-

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 find that multipliers are larger in recessions but Owyang *et al.* 2013 and Ramey & Zubairy 2018 find little support for higher multipliers in high states of unemployment.) "Learning by necessity" provides a different mechanism through which fiscal policy may depend on slack in the economy. In this regard, the paper relates to policy debates on the limits to non-inflationary monetary and fiscal stimulus. These have often been framed in the context of the slope of the Phillips Curve (cf Hazell *et al.* 2022) and the trade off between unemployment and inflation. Some have also speculated that allowing factor markets to operate under "high pressure" may stimulate productivity and innovation. (See the discussion in Bernstein & Bentele 2019, who point to a dearth of evidence on this question.) Boehm & Pandalai-Nayar (2022) show that supply curves are convex, but I provide evidence that sufficiently high demand may be able to shift the supply curve, not only shift along it.[9]

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. The observation of a learning curve was ingrained in the post-war conventional wisdom and was one of the motivating facts of the endogenous growth literature (cf. Arrow1962, Lucas 1993, Young 1991; Romer 1994 and Akcigit & Nicholas 2019 for literature reviews).[10] Learning by doing and economies of scale both imply that fiscal policy or other sources of demand may increase firms' productivity either cyclically or persistently. However, learning curve estimates in this early literature are based on correlations, with the obvious problem that plants with greater productivity growth will have accumulated larger volumes of output over time. In contrast, I use strategic shifts in demand for broad aircraft types as a source of variation in production that isn't driven by a specific plant's productivity.[11]

Argote & Epple (1990) show that manufacturing firms vary greatly in the extent to which they

ifornian economy. Jaworski (2017) and Garin & Rothbaum (2022) study the effects of wartime public investments on longer-term development. Hanlon & Jaworski (2021) study product improvements in the interwar US aircraft industry, but their focus is on the role of patent protections, rather than demand, on innovation. There is of course an extensive literature on other economic implications of the war, including on gender (Goldin & Olivetti 2013), management (Bianchi & Giorcelli 2022), and R&D (Gross & Sampat 2020). See Rockoff (2012) and Fishback & Jaworski (2016) for reviews.

[9]It is natural to ask whether the wage and price controls of World War II limit the external validity of this context to more recent high-pressure economic environments. As I discuss in the following section, price controls didn't apply to aircraft manufacturers and productivity growth led to dramatic *declines* in the prices of complete aircraft.

[10]A literature in macroeconomics has estimated returns to scale in aggregate production functions (Hall 1990, Burnside 1996, Basu & Fernald 1997). The importance of market size on productivity has also been emphasized in the literature on international trade and innovation (Acemoglu & Linn 2004; Finkelstein 2004 De Loecker 2007, 2011; Atkin *et al.* 2017 Melitz & Redding 2021), but these focus on the long-run, as opposed to business cycle frequency and don't speak to importance of capacity utilization. Further, the mechanism is typically through the selection of more productive firms as the market expands, rather than productivity gains within firms, as documented in this paper.

[11]See Benkard (2000) and Levitt *et al.* (2013) for other instrumental variables approaches. The former studies a single modern aircraft plant and uses lags of global GDP and oil prices as instruments for demand. The latter studies a single automobile plant and uses the cumulative production of other shifts as an instrument for the cumulative production of a given shift.

gain productivity with experience. I document a new dimension of heterogeneity, where "learning by doing" occurs primarily when plants face tighter capacity constraints. In his surveys of the the literature on learning by doing, Thompson (2010, 2012) makes the distinction between passive learning and active measures to improve productivity as scale increases. Most existing work on learning by doing gives little indication as to how it is that plants enhance productivity as experience accumulates. Here, I document measures taken by plants to improve production methods, supply chains, and limiting labor disruptions.

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 1994, 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.

The remainder of the paper is organized as follows. Section 2 describes the data and the historical and institutional setting. Section 3 lays out the empirical strategy with the main results shown in Section 4. Section 5 gives a historical discussion 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 led to the largest cyclical increase in public consumption in US history. Figure 1a shows government consumption as a percent of GDP in the US from 1929 to today. The Second World War stands out as the single largest shock to government purchases.[12] 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 clear that by the time the US officially entered the war in late 1941, the economy was close to full employment (Figure 1b). Gordon & Krenn (2010) evaluate that the economy had no excess capacity by 1941 so that the scope for Keynesian fiscal expansion was already exhausted. (See Long 1952 for a discussion of employment trends during the war.) Throughout the period studied, the US economy was operating at high employment rates and high utilization rates. However, there were large differences in slack across plants and regions at the onset of the production drive and throughout the

[12] Neither the recent Covid-related relief programs nor recently passed and recent spending bills change this picture. The former were mainly transfers rather than government consumption or investment. The latter are spread over eight to ten years, so that they will amount to less than 0.5% of annual GDP.

war. I will use these differences in studying heterogeneous responses to demand depending on utilization.

The analysis that follows focuses on aircraft purchases, narrowing the analysis to a single sector. However, aircraft was the single largest expenditure item in the military budget and became the largest industry during the war. Figure 1c shows that aircraft procurement peaked at ten percent of pre-war GDP, a share of GDP that is comparable to *total* defense spending at the peak of the Vietnam War. In May 1940, after the fall of France, President Roosevelt set an ambitious objective of producing 50,000 planes during the war.[13] At the time, this was viewed as a nearly impossible task, with economists Robert Nathan and Simon Kuznetz estimating that the US didn't have the productive capacity to meet this aim.[14] In actuality, the US aircraft industry produced twice this number of aircraft in 1944 alone (War Production Board 1945 p. 10). Procurement of aircraft (and other war materiel) increased during 1940-41, but only took off following the attack on Pearl Harbor in December 1941; it peaked in 1943. The aircraft industry was a young industry: the average firm was founded in 1927 and the average plant was founded in 1934.

Procurement was under the purview of the relevant military branches, in this case the Army Air Force (AAF) and the Navy. During the war, procurement was also coordinated with the War Production Board (WPB), which provided the overall strategy for the war production effort. Because of the importance and ambition of the aircraft production schedule, procurement of airframe, motors, and propellers was separated from the general Army Supply Program and was managed by a special agency, the Aircraft Resources Control Office, in Dayton Ohio. This agency dealt directly with the industry and the WPB. The AAF base at Wright Field (later Wright-Paterson) monitored aircraft production and aircraft modification. The majority of contracts were Cost Plus Fixed Fee (CPFF), whereby the suppliers' (audited) costs were reimbursed and augmented with a pre-negotiated payment per aircraft delivered. However, because of concerns of war profiteering, markups were restricted by law (to 4% by the end of the war), many contracts were renegotiated ex-post, and most aircraft manufacturers' profit margins were lower than they were before or after the war.[15]

Aircraft firms, their subcontractors, and their suppliers were exempt from wartime price controls. Wages were regulated and frozen at their March 1942 levels. Wages did increase during the war, but all wage increases required government approval (Smith 1991 pp. 399-403). Prior to the war, most aircraft were made to order based on detailed specifications of the procuring agency. These production methods were untenable given the quantities of aircraft demanded in wartime.

[13]Fireside chat, May 26 1940. (See Smith 1991 page 129 for a discussion.)

[14]Wilson (2018) p. 178. This what part of what has been called the "feasibility dispute", where military commanders demanded munition production beyond what contemporary economists believed was feasible. See Nelson (1950) pp. 376-81, Brigante (1950), and Smith (1991) p.154.

[15]Smith (1991) pp. 248-293. See Wilson (2018), chapter 4, for a history of contract re-negotiations.

To facilitate mass production, the AAF and WPB agreed to purchase standardized aircraft models from aircraft manufacturers. These were then modified in army or navy modification centers to the specifications of the procuring agency. This aides productivity analysis as one can be more confident that an aircraft of a specific model and mark coming off of a specific production line had the same specifications. The following section outlines in detail how purchases were allocated across plants, which is central to identifying the effects of aircraft demand on plant productivity.

The analysis in this paper draws on a number of archival sources, primarily from the archives of the WPB, the War Manpower Commission (both at the National Archives, College Park, MD), the Air Materiel Command of the AAF (Air Force Historical Research Agency–AFHRA, Maxwell Air Force Base, AL), and the National Aircraft War Production Council (Truman Library, Independence, MO). While several of the sources have been used in previous research, I have digitized new materials and matched several data sources. Some data, including capacity utilization measures, have not been used in previous academic research. Here, I briefly outline the data sources for the variables used in the analysis that follows. Full details are provided in the data appendix.

The main productivity measures are from the Aeronautical Monthly Progress Reports (AMPR), collected by the AAF headquarters at Wright Field. The WPB and AAF carefully monitored the production of war materiel. All aircraft manufacturers were required to provide monthly reports on production progress. The data are for assembly of complete "standardized" aircraft (pre-customization and modification). The AMPRs were used to monitor production against schedules, to ensure that manufacturers were utilizing capacity, and to monitor costs for CPFF contracts. For these reasons, aircraft manufacturers were frequently audited to ensure accurate reporting.[16] Reporting requirements and methodology were uniform across plants and extremely detailed. Figure A.1 in the appendix shows one of the standardized forms that all manufacturers had too fill.[17]

The AMPR includes monthly plant by aircraft-model data for all wartime aircraft manufacturers. 61 plants produced 83 different aircraft models leading to 204 plant-by-model combinations. To ease exposition, I will slightly abuse terminology in what follows and refer to a plant-by-model combination as a "production line", although some plants ran several production lines for the same model. Aircraft models are narrowly defined in the data and all design changes are noted. I dropped a small number of plants and production lines that produced fewer than 100 aircraft cumulatively or operated for less than 6 months, as they don't provide sufficient production-line

[16] District procurement offices were assigned to monitor these reports and were given formulae to detect misreporting. Wilson (2018) documents (p. 176) that as many as 60 military and GAO auditors could be on site to monitor production at a single airframe plant. See "AMPR Questionnaire for use in Making In-Plant Audits of Basic Labor Statistics" (AFHRA archives, Reel A2050, starting on slide 1128) and "Basic Labor Statistics–How to Maintain Them", ibid, starting on slide 1179.

[17] The AAF also gave plants a 150 page document with minute detail on how to report production, productivity, capacity utilization, and other data in a uniform format. The document, ATSC Regulation No. 15-36-3, can be found in the AFHRA archives, Reel A2050, starting on slide 850. See also San Diego Air and Space Museum (SDASM) archives Box 34 to see how a specific manufacturer (Consolidated Vultee) adopted these procedures internally.

level variation.[18]

The point of departure for productivity measurement is the variable "Unit Man Hours: Entire Plane". Plants reported the number of direct worker-hours that entered into the production of the last plane delivered in each calendar month. This includes only workers directly involved in manufacturing; overhead was separately reported as "indirect workers". The measure includes hours worked in sub-assemblies, so that it gives a consistent comparison when producers outsourced parts of the production process.[19] The variable gives hours per physical units of output and at the product level, addressing the multi-product plant problem. While there are clear advantages to measuring productivity at the aircraft level, the last aircraft may be unrepresentative of the plant's average productivity. For sake of comparison, I calculated monthly labor productivity by dividing the number of aircraft delivered by payroll hours for manufacturing workers as is commonly done. The two measures are highly correlated but the comparison also highlights the advantage of direct aircraft-level productivity measurement. The typical aircraft took more than a single month to build and hte aircraft-level measure incorporates hours in all production months.[20] In contrast, dividing the number of aircraft by hours worked in the current month creates a mismatch between delivery time and production time and severely misstates productivity at the beginning or end of a production batch. (The former shows many workers producing little output and the latter the opposite.)[21]

The AMPR provides a physical proxy for capital. It gives quarterly observations of the floor space utilized in production in each plant. The measure includes only floor space actively used for

[18]The AMPR begins reporting in 1941, but has only 60% coverage prior to 1943. Coverage is 100% starting in January 1943, which was also the initial production date for a large share of production lines.

[19]The AMPR 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.

[20]The AMPR notes that "Man-hours per unit take into consideration all hours necessary to complete a plane regardless of whether these hours are spent during the month of completion (report month) or over a period of several months." Documents from Convair, the largest wartime producer, show that bombers required 45 to 90 days to build, depending on the model (SDASM archives, Box 17).

[21]The number of monthly aircraft delivered by plant and model is given in the AMPR. The same information is available in Civilian Production Administration's *Official Munitions Production* (OMP). This post-war document recorded all major munitions procured by all military branches during the war at monthly frequency. It gives the number of aircraft "acceptances" delivered to the military by model from each aircraft plant. This document is slightly more comprehensive than the AMPR, with the latter reaching 100% coverage only in January 1943. I use this source to fill in observations missing from the AMPR and to cross-check the AMPR's data. For those months and production lines where both sources report aircraft deliveries, the two sources correspond closely. The AMPR is used as the primary source for monthly production and the OMP is the secondary source, used only in months when AMPR data are unavailable. This approach maximizes coverage, but results are robust to using either of the individual sources.

production and therefore incorporates capital utilization to some degree. It excludes office space and other non-production facilities but includes any yard space used for production. A quantity-based measure of the capital stock has several advantages. Structures were the largest component (60%) of capital investment in the airframe industry during the war. However, expenditure on structures confounds variation in land prices and construction costs across regions (expenditure on structures) with real differences in the capital stock (physical structures). Second, capital expenditure data requires an estimate of the initial capital stock. In contrast, floor space is measured in square-feet, giving a stock, rather than a flow, measure of the quantity of structures in use.

The capital stock is relatively slow-moving in the data and I interpolate quarterly floor space to give a monthly measure of physical capital per plant. While production, labor inputs, and productivity are measured at the production-line level, capital is at the plant level. I allocate capital across production lines 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.[22] Using product-level labor inputs, TFP is measured residually from a Cobb-Douglas production function with a capital share in production of $\frac{1}{3}$.

Of course, floor space doesn't produce aircraft on its own and plants varied in the amount and quality of equipment used in production. Fortunately, plants recorded all investments in plant and equipment exceeding $25,000, which we use as a measure of capital deepening. As we will see, investment in structures is strongly correlated with investment in equipment and both are highly correlated with physical floor space *nine months later*. This lag between investment expenditure and installed capital highlights another advantage of using a real-time measure of capital rather than capital stock imputed from investment.

Figure 2 shows the time series of aggregate aircraft production, hours worked, and capital (floor space), from 1942 to 1945, all relative to their January 1942 values. Production is shown as number of aircraft in the top panel and in total aircraft weight in the bottom panel. For contemporary researchers, this latter measure was the common way to adjust for larger aircrafts' greater production complexity. The figures give prima facie evidence of the great increase in productivity during the war. Hours worked and capital grew in tandem by a factor of close to 2.5 (roughly 0.9 log units). In contrast, the number of aircraft produced increased by a factor of 3.5 (1.25 log units). This suggests a TFP increase of 35%, if the industry production function is homogeneous of degree one. The increase in TFP measured in units of aircraft weight is even more dramatic:

[22]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 moving from one production line to the other. It also assumes the same capital intensity across production lines, which is difficult to verify. In theory, one could allocate capital so as to equalize the revenue productivity of capital across production lines. However, I don't observe prices or revenue at the production line level at the monthly frequency of this study and the ratio of capital to aircraft shouldn't be expected to equalize across aircraft models of differing complexity.

roughly 250%.[23]

The detailed data collected in the AMPR also give a rare account of capital and labor utilization in all plants of the nation's largest industry. The statistics include the number of work shifts per day, the number of daily hours in each shift, and the number of monthly worker-hours active in each one of the shifts per month. From these, I calculate shift utilization, which was used to assess capital utilization during the war and suggested by Basu *et al.* (2006) as a measure of capital utilization. A plant's capacity in a given month is assessed using the number of *scheduled* working hours in the first (Monday morning) shift (always the most active shift) as indicative of full production potential in that week. Full capacity is then measured as the number of weekly work hours that would result if the plant were active 24 hours a day at full production potential (i.e. with the same number of workers per hour as the first shift). Capital utilization is the ratio between *actual* monthly work hours and full capacity.[24] The AMPR also includes monthly reports of average weekly hours per worker, which I use as a measure of labor utilization.[25]

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% by the end of 1942. 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 arrival of the "year of production" in 1943 (Klein 2013) sees a surge in aggregate productivity (Figure 2), but a rapid *decline* in capital utilization through the remainder of the war. This is a first indication 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 Figure 3 shows that workers were also strained early in the war, with the average production worker in the median plant working nearly 50 hours a week in 1942. Like capital utilization, labor utilization declines sharply in 1943, stabilizing at around 45 hours a week.[26]

[23] Field (2008), however, argues that TFP declined for the US economy as a whole during this period and argues in Field (2018, 2002) that the war led to substantial mis-allocation across industries that led to lower post-war productivity. This paper focuses on a single industry, so is silent on this issue. However, Appendix Figure A.2 shows that the productivity dispersion across WWII plants declined over the course of the war.

[24] 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. Of course, there is also variation over time within plants in the number of hours employed in the first shift. However, this will already be captured in the capital to labor ratio.

[25] Shift utilization is imperfectly correlated (with a coefficient of 0.5) with hours per worker. 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 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).

[26] Average, as opposed to median hours worked show a similar decline in hours per worker. Slight differences between the numbers reported here and those in Levenson (1944) are because the latter reports hours for *all* workers,

3 Empirical Strategy

Estimating scale effects in production, learning by doing, and the effects of public demand on plant productivity pose an empirical challenge. Productivity is one reason why some plants gain larger scale, accumulate more experience, and attract more procurement contracts. Hence simple correlations between productivity and scale aren't necessarily informative of demand's causal impact. The post-war learning-by-doing (LBD) literature reported correlations between cumulative output and output per worker as reflecting a "learning curve". In doing so, researchers implicitly presumed that wartime procurement reflected a demand-shifter that traced the supply curve or production function. However, procurement wasn't randomly allocated across plants and time and the government likely purchased more aircraft from those plants it believed could deliver, i.e. ramp up production, in relatively short order.

Reverse causation isn't merely a theoretical possibility. It is also very likely. Figure 4a shows a scatter plot each production line's (log) cumulative output up to VE day, May 1945, against its (log) labor productivity 16 months earlier (the farthest back one can go without losing newer production lines). The strong correlation between *past* productivity and cumulative output *at the end of the war* obviates the point that high- productivity plants accumulated more production. Productivity is highly auto-correlated in the data, as seen in Figure 4b. Current productivity is correlated with *past* productivity, which is in turn correlated with, and likely causes, cumulative production–often taken as a proxy for experience or learning. The correlation between terminal productivity and experience confounds "learning by doing" with the fact that plants that were initially more productive accumulated more experience and these plants continued to be more productive to the end of the war.

In the parlance of modern econometrics, estimated learning curves suffer from substantial pre-trends. These pre-trends are illustrated in Figure 5, which shows the regression coefficient in a standard LBD regression with pre- and post-trends. These show the coefficient when regressing (log) labor productivity (aircraft per hour) on experience (log cumulative production). The regression includes month and production line fixed effects. The response at horizon $h = 0$ is the coefficient that is typically reported in the literature, giving the percent increase in relative productivity seen in a production line with 1% more experience. Responses at horizons $h < 0$ show the association 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. It may well be the case that the higher cumulative production at time zero is the result of previously high productivity. Responses at horizons $h > 0$ show the association between current experience and *future* productivity. If anything, productivity *declines* (in relative

while I report numbers for *manufacturing* workers, which are more relevant for the purpose of this paper.

terms) in the months after a plant gains more (relative) experience.[27]

To add to the challenges of estimating an experience curve, production is also autocorrelated, so that *cumulative* production is highly correlated with *current* production (Figure 4c), making it difficult to disentangle "learning by doing" from scale effects. The local projection regressions that follow will control for lagged production to control for the pre-trends documented here. But once we control for lagged production, there is almost no difference between an innovation to current and cumulative production.[28]

In the analysis that follows, I instrument the monthly production of each individual production line (plant-by-model combination) with the aggregate production of all other production lines producing the same broad aircraft type in that same month. This approach relies 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 procurement 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_{mpt} for demand D_{mpt} for aircraft model m in plant p in month t is given by $I_{mpt} = \sum_{\pi \neq p} \sum_{\mu \in \mathbb{M}_m} D_{\mu \pi t}$, where $\mathbb{M}_m$ is the set of aircraft models of the broad type that includes model m. The first stage of the 2-stage least squares specification is given by

$$D_{mpt} = \gamma I_{mpt} + \text{FE} + \text{lags} + u_{mpt}. \tag{1}$$

Impulse responses of the second stage of the regression are estimated using local projections (Jordà 2005). At each horizon h, the response of productivity $y_{mp,t+h}$ to aircraft demand D_{mpt} is estimated as $\hat{\beta}_h$, arising from the regression

$$y_{mp,t+h} - y_{mp,t-1} = \beta_h \widehat{D}_{mpt} + \sum_{\ell=1}^{L} \delta_\ell^D D_{mpt-i} + \alpha_t + \alpha_{mp} + \varepsilon_{mpt}, \tag{2}$$

where $\hat{D}_{mp,t}$ is predicted aircraft demand from (1). α_t and α_{mp} are time and plant-by-model (production line) fixed effects, respectively. Two-way fixed effects imply that we are comparing the differential productivity growth over time across production lines and gives estimates a difference-in-differences interpretation. Reported regressions include $L = 6$ monthly lags of aircraft production.

[27]These lead-lag relations would also give the impression that "learning" is followed by "forgetting", as is the case in many LBD studies.

[28]Table A1 in the appendix shows results of traditional learning by doing OLS regressions using our data. They include time and production line fixed effects. When controls for current and lagged production are added, there is no statistically significant correlation between cumulative production and productivity, illustrating the challenge of disentangling experience and scale effects.

Controlling for the lagged explanatory variable is common practice in time series econometrics and turns out to be important to eliminate pre-trends in productivity. Once one controls for lags of production there is little difference between cumulative and current production, but formally the regressions estimate the effects of current production scale, rather than experience, on productivity. We will revisit this distinction in the following section.

Instrument relevance requires that the timing of production is correlated across production lines producing the same type of broad aircraft. Relevance is borne out in F statistics reported in the figures of the following section. Non-compliance could arise if a plant lost orders to others because of low productivity and this is precisely the variation that the instrument attempts to discard. Conversely, the instrument discards idiosyncratic surges in production in an individual production line, which may be caused by higher productivity.

The exclusion restriction requires that the national demand for other models of a broad aircraft type affects the (relative) subsequent productivity growth in the the production line in question only through the demand directed to that production line.[29] In assessing the validity of the instrument, let's consider the source of variation it captures. This is illustrated in Figure 6, which shows the average number of aircraft delivered per production line in four aircraft types: bombers, fighters, transport, and training. The figure shows that the four categories saw very demand different fluctuations, which have known historical interpretations. Early war production was for lend-lease assistance to US allies in Europe. In terms of aviation, this primarily came in 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 in the immediate aftermath of the attack on Pearl Harbor anticipated a heavy reliance on aerial bombing (as exemplified by the Battle of Midway in summer 1942), leading to an inflection in the demand for bomber aircraft in 1942 and surge in demand in 1943.[30]

Demand for transport aircraft took off only later, in the ground operations phase of the war: transport aircraft supported the island-hopping operations in the Pacific and facilitated the invasion of Italy in 1943.[31] Demand for fighter aircraft surged again in 1943, as can be seen in the figure,

[29]Stock & Watson (2018) add a third identifying assumption for local projections IV estimation, lead-lag exogeneity: the instrument may not be correlated with leads or lags of errors, in our context $E[I_{mpt}]\varepsilon_{mpt+j}|X_{mpt} = 0$, for all $j \neq 0$ where X_{mpt} are controls. They suggest an informal test: the instrument should be unpredictable in a regression on the lags of the outcome variable, in this case productivity. Indeed, conditional on the controls (which include six lags of demand), 12 lags of productivity are uncorrelated with the instrument. This is related to the requirement that there be no pre-trends, which will be reported in the following section.

[30]Edgerton (2012) claims that US military planners only fully appreciated the full import of bombers for military strategy during the Battle of Britain, but that British leadership viewed strategic bombing as central to their strategy. This meant that the UK was relatively self-sufficient in bomber production and the US only had to produce bombers massively with their direct involvement in the war.

[31]See AFHRA 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 the importance of transport

when it became apparent that both bomber and transport aircraft benefited from fighter escorts.[32] Trainer aircraft were naturally required more in the early war years than later in the war.

A threat to identification would arise if these relative demand shifts were due to differential expected productivity growth across broad aircraft types. The historical literature gives strong indications to the contrary: Strategic considerations were paramount in determining procurement schedules for broad categories of munitions. In September 1943, a report by the WMC on *Manpower Problems in the Airframe Industry*[33] notes that

> 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.

Towards the end of the war, a WPB report[34] looks back and summarizes:

> 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 report 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

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.

[32] Major Lesher, Lee A. (1988). "The Evolution of the Long-Range Escort Doctrine in World War II" United States Air Command and Staff College. Support for this doctrine was gaining traction and led to increased fighter demand in early 1943. But an important inflection point was a failed AAF strategic bombing mission on Schweinfurt, Germany in August 1943. The targets were beyond the range of fighters and led to a loss of 60 out of 376 participating bombers. Strategic bombing was curtailed for several months as a result and the view that bombers must receive fighter escort became entrenched for the remainder of the war. See also Baxter (1946) for a similar argument.

[33] War Manpower Commission, Sep 1943, National Archives College Park.

[34] WPB Production in 1944.

most able to deliver. But this source of variation is discarded, rather than captured by, the 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 terms of military operations.

Finally, I note that the instrument doesn't dispose of the need for two-way fixed effects. Absent time fixed effects, the reduced-form of the IV would correlate production of broad aircraft type and productivity late in the war relative to early in the war. But productivity gains from all sources–not only due to increased demand–will have lead to increased production over the war: the reverse direction of causation. Similarly, absent cross-sectional fixed effects, we would be including persistent differences in productivity and quantity produced across broad aircraft types. At the most pedestrian level, productivity measured in aircraft per hour worked isn't comparable across different aircraft models with substantial differences in complexity. Model fixed effects (incorporated in the plant by model fixed effects) are crucial to ensure we are comparing differential productivity growth rather than levels of aircraft per hour across very different aircraft types.

Learning by Necessity Regressions

Once we have established the causal effect of government demand on productivity, we will investigate heterogeneity with respect to capacity utilization. The learning by necessity hypothesis is that plants see greater productivity growth following a demand shock if they are operating at higher rates of utilization. Taking capital utilization as an example, the variable c_p is assigned a value of one if plant p had an above median initial value of capital utilization.[35] I then use the following triple differences in differences estimator to investigate the differential effects of demand depending on initial capital utilization:

$$y_{mpt+h} - y_{mpt-1} = \beta_h^{3D}[\widehat{D_{mpt} \times c_p}] + \omega_h \widehat{D}_{mpt} + \text{lags} + \text{FE} + \varepsilon_{mpt}^{3D}. \tag{3}$$

As in (2), $\widehat{D}_{mpt}$ gives demand for aircraft of model m from plant p in month t, predicted by the instrument in the first stage of the two-stage least squares. However, the coefficient of interest is now β_h^{3D}, on the interaction between demand and the capacity constraints indicator c_p, giving the increase in productivity in high utilization plants, above and beyond the productivity growth in plants with lower rates of utilization, following a shock to government demand. The coefficient ω_h gives the response for plants with lower utilization. Demand D_{mpt} and its interaction with capacity

[35] I take the first available observation for each plant, which is typically the first month they delivered aircraft for the war production drive. This initial date differs across plants. Setting the dummy based on the January 1943 value or the average value over the war gives similar results.

constraints c_p are jointly projected on the leave-one-out instrument I_{mpt} and its interaction with the capacity constraint dummy in a first stage analogous to (1). The capacity constraints dummy itself is excluded as its variation is absorbed by plant by model fixed effects. FE represents month and plant-by-model (production line) fixed effects.

While we use an instrument to address endogenous government demand for aircraft, the heterogeneity variable of capacity utilization may be confounded with other factors. The additional identifying assumption in the triple difference specification is that high-utilization production lines see greater productivity gains following a demand shock because of their high rates of capacity utilization, not due to another correlated factor that may also lead heterogeneous effects. We discuss and control for potential confounders in the following section.

4 Government Demand and Productivity Growth

The framework introduced in the previous section is now used to estimate the dynamic response of output per hour worked to a 1% increase in demand. The local-projections impulse response is shown in Figure 7a. The shaded areas in this and subsequent figures give 90% and 95% weak-instrument robust confidence bands.[36] Regressions include time and plant-by-model fixed effects and are normalized to productivity at time $t = -1$. Responses therefore 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 logs of) production. Labor productivity increases by around $\frac{1}{3}$ of a percent per each percent increase in demand, within the first 12 months.

Figure A.3 in the appendix shows labor productivity's pre-trend before the shock to demand. There are perhaps signs of a slight pre-trend in productivity in the runup to the shock, but panels (b) and (c) of the same figure show that the pre-trend is eliminated when including region-specific time fixed effects or controlling for lagged capital per worker, without substantively changing the responses at horizons of $h > 0$. Estimates become very noisy beyond the reported horizon because of the decreasing sample size. It is therefore difficult to ascertain the duration of the response.[37] [38]

[36]The instrument is sufficiently strong, by standard criteria, with a heteroskedasticity-robust (Montiel Olea & Pflueger 2013) F-statistic of 30 in the 12-month horizon regression. F-statistics for subsequent regressions are reported in the figure notes. In any case, I follow Andrews *et al.*'s 2019 recommendation and report weak-instrument robust (Finlay & Magnusson 2009) standard errors in all figures.

[37]Exiting firms or plants could lead to survivorship bias. However, because of the enormous demand for aircraft, only three plants exited during the war: Howard aircraft in Chicago; Interstate aircraft in El Segundo, CA; and St. Louis Aircraft in St. Louis. Results are virtually unchanged when excluding these three plants from the analysis.

[38]Figure A.4 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 WPB may have directed demand towards plants it expected to deliver aircraft 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 WPB was more concerned about a plant's ability to deliver a large quantity of aircraft than plants'

Figure 7c shows the relative response of production itself to the 1% (relative) increase in demand. The initial shock to aircraft demand leads to a persistent surge in production. Figure 7a should therefore be seen as reflecting the response of labor productivity to a one-off increase in demand with a half-life of roughly a year.

The strong correlation between current and accumulated output, noted in Section 3 and shown in Figure 4c, makes it difficult to disentangle learning effects (responses to cumulative production) from scale or demand effects (responses to current production). Once we control for lagged demand in (2), a shock to one is nearly identical to a shock to the other.[39] Nevertheless, Figure A.5a in the appendix shows the impulse response of identified demand shocks when controlling for cumulative experience (the log of the production line's cumulative production, $\text{Experience}_{mpt} = \log\left(\Sigma_{s=0}^{t} exp(D_{mpt})\right)$). Results are similar to the baseline specification.[40] In contrast, Figure A.5b in the appendix shows the response of labor productivity to a 1% increase in experience, as in a traditional LBD regression, but using the fixed effects, local projections IV specification and controlling for current production.[41] The response of labor productivity to "experience" is extremely transient once one controls for current production.[42]

This analysis isn't meant as a wholesale rejection of learning by doing in favor of scale effects, or of dynamic in favor of static scale effects. I reiterate that the two are difficult to separate because their mechanical collinearity and the result in Figure A.5b may result from having a better instrument for current than for cumulative demand. Further, the specification controls for 6 lags of aircraft demand, necessary to eliminate pre-trends, so that cumulative production is residualized from the recent half-year of production. The results may therefore be consistent with learning in face of substantial forgetting. Further, plants may have learned from others, a factor that is absorbed by the two way fixed effects. Such positive spillovers would mean that the estimates reported here are lower bounds on both the internal and general equilibrium responses of productivity to demand.

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cost/productivity. This objective, together with the WMC's goal of directing demand to lower-pressure labor markets, could have in fact shifted demand to lower productivity plants, leading to a downward bias in OLS.

[39] Their magnitude is different, however, in a log-log specification. A one percent shock to cumulative output is far larger than a one percent shock to demand, when measured in number of aircraft. Regressions on cumulative output also put a greater weight on shocks early in the war because they are measured relative to cumulative production, which increases over time.

[40] Results are also similar when controlling for learning and *forgetting* as in Benkard (2000) or Thompson (2007), using a forgetting rate of 5% per month as found in the former. Other forgetting rates yield similar results. Of course, as the forgetting rate approaches 100% per month, there is no distinction between "experience" and current demand.

[41] To make the two regressions comparable, we instrument for experience using the cumulative equivalent of the instrument outlined in the previous section, i.e. we instrument cumulative demand for aircraft in production line mp in month t using the cumulative national production of aircraft of the same broad type, excluding the production line in question. The validity of the instrument is less obvious in this case, because it is plausible that the *cumulative* demand for and production of bombers relative to fighters, to take an example, was determined by relative technological progress. This concern is less acute at the higher frequencies exploited in our main estimates.

[42] The larger scale of the short run response is expected given that the magnitude of a 1% shock to *cumulative* production is enormous compared to a 1% shock to *current* production.

Increases in production and in output per hour worked were associated with massive investments in facility expansions as we saw in Figure 2. Although the figure shows that aggregate hours worked grew at a similar pace to capital, leaving the capital-labor ratio constant for the average plant, it is possible that investments were directed to plants facing high demand so that labor productivity grew in these plants due to higher capital per worker. Figure 7b shows the response of TFP to a 1% increase in relative demand, with the fixed-effects LPIV specification of (1) and (2). The increase in TFP is of similar magnitude to that of labor productivity.[43] [44] [45]

TFP is calculated using the square feet of facilities used in production, a physical measure of capital. Although structures reflected more than 60% of the capital stock of aircraft plants during the war, structures alone don't produce airplanes and Thompson (2001) has shown that capital deepening explains a large part of the productivity growth in shipyards during the war. Fortunately, the WPB recorded every investment in plant expansion at the plant level exceeding $25,000 during the war, whether publicly or privately financed, and these investments are separated into "structure" and "equipment".[46] TPF's response to a demand shock is nearly identical when controlling for each plant's cumulative investment in equipment. The result of this regression is reported in Table A2 in the appendix, alongside additional robustness checks to be discussed below. TPF grew in response to demand, even when considering capital deepening.[47]

A look at the correlation between these various measures of capital show why this control makes little difference, but is also illustrative of the importance of a measure of physical capital stock, as opposed to cumulative investment often used in the literature. Figure A.6 in the appendix shows that there is almost no correlation between floor space used in production and cumulative investments in structure, after controlling for time and plant fixed effects.[48] Rather it is *past* investments in structures that are highly predictive of floor space used, with the correlation peaking at a 9-month lag. This shows a nearly year-long lag between the time of investment and the time the investment is put to productive use. Capital investment data therefore gives incorrect measures of TFP, particularly in two-way-fixed-effects specifications and at higher frequencies. That said, given

[43]TFP is calculated as the residual from a Cobb-Douglass production function with a capital share of $\frac{1}{3}$. Results are similar when simply controlling for capital per hour worked.

[44]The slightly stronger response of TFP than labor productivity to a demand shock reflects the fact that output remains elevated following the demand shock, as seen in figure 7c, but the capital to labor ratio peaks (in plants receiving the demand shock relative to others) at the time of the demand shock and gradually declines thereafter, so that subsequent production is performed with less capital per hours (because hours continue to rise while capital remains nearly constant). Labor productivity growth associated with a decline in the capital-labor ratio means that TFP is rising faster than labor productivity.

[45]Figure A.3 in the appendix shows that there is no pre-trend in TFP, although error bands are wide.

[46]War Production Board, *War Manufacturing Facilities Authorized by State and County*, National Archives, College Park, MD.

[47]Results are similar when allowing for a constant depreciation rate.

[48]They are highly correlated in the raw data, but this is mostly because of cross-sectional differences in plant size and the trend growth in capital investment and floor space over the war. The fixed-effect specification illustrates that plants' relative growth in floor space use isn't correlated contemporaneously with their relative pace of investment.

the extremely strong correlation between the 9-month lag in cumulative investment in structures and current floor space, results are nearly identical when using one or the other as a measure of the capital stock. Further, the figure shows that investments in equipment/machinery are nearly perfectly correlated (contemporaneously) with investment in structures (even after controlling for two way fixed effects). The near perfect correlation between investment in structures and equipment means that capital deepening is unlikely to affect measurement of TFP that accounts for floor space, and why controlling for investment in equipment does little to affect the results.

Capital is measured by *active* floor space used. This already accounts to some extent for capital utilization, but the impulse response in Figure 7b derives from a specification that also controls for capital utilization, measured by shift utilization, 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).[49]

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, with aircraft models re-coded at every design change. This means that results also largely control 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.[50]

Recent research has warned of potential bias in two-way fixed effects regressions, particularly if treatment effects are heterogeneous. An estimator proposed by de Chaisemartin & D'Haultfoeuille (2020) corrects for this bias, but requires a set of groups (in our case production lines) whose treatment status doesn't change from period to period, a condition that doesn't apply in this setting, where production typically changes every month in every production line. 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. He shows that heterogeneous-treatment bias is more likely to arise with (late) comparisons between groups that were treated late with those treated early. Plants received procurement orders throughout the war and it is therefore impossible to separate production lines into those treated early and late. However, Figure A.8 in the appendix shows impulse responses in a specification that offers a partial solution to the concern. It interacts the leave-one-out instrument of the previous regressions with a dummy variable equalling one in first half of the sample. This instrument compares shocks to relative demand across production lines early in the war. The instrument ignores variation between production lines facing greater

[49]The responses are very similar excluding the control for capital utilization. See Figure A.7 in the appendix.

[50]Results might overstate productivity growth if demand pressures caused plants to cut corners and produce lower quality aircraft.

demand later in the war with those receiving less demand late in the war, but which possibly saw high demand early on, and therefore carry-forward their productivity gains induced by early-war demand. This is an informal application of the Goodman-Bacon (2021) methodology to a setting with continuous, as opposed to discrete, treatment status. Results are similar, albeit with wider standard errors, allaying to some extent the concern that the baseline results were biased due to heterogeneous treatment effects.[51]

Several robustness exercises are shown in Table A2. The top panel of the table shows responses of output per hour worked at the twelve-month horizon following a shock to aircraft demand and the bottom panel shows a similar response for TFP. The first two columns give the 12-month response for OLS and IV specifications. Column 3 of the table shows responses in a specification that replaces time fixed effects with time-by-region fixed effects. I include three regional dummies for west coast, east coast, and the rest of the country. Column 4 reports a specification controlling for cumulative aircraft production, as in Figure A.5a in the appendix. Column 5 controls for cumulative capital investment in machinery. Column 6 controls for plant age, to address the possibility that demand, whether current or cumulative may be higher in older plants, who may also differ in their productivity. Finally, Column 7 reports a specification where observations are weighted by a production line's size, given by their cumulative production over the entire course of the war.

Government Demand, Capacity Constraints, and Productivity Growth

Having documented how demand affects productivity in the average aircraft plant, I now show important heterogeneity in responses to increased demand. The focus will be on the role of capacity utilization, what I have called "learning by necessity". The regressions follow the specification in (3). To begin with, I consider capital utilization: The dummy variable c_p is assigned a value of one if plant p had an above median initial value of capital utilization.

Figure 8 plots the local projections impulse response: the estimated β_h^{3D} coefficients. This represents the response of productivity to a one percent increase in demand (predicted by the instrument) in plants with higher initial capital utilization relative to those with initially low 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 0.2% more in plants that were initially more constrained.[52]

[51] When restricted to the first half of the sample, the instrument becomes weak, leading to wider weak-instrument robust standard errors. The horizon in the figure is restricted to 12 months, with first stage F statistics declining rapidly with the horizon.

[52] As a general proposition, standard errors in heterogeneous effects specifications of this sort will tend to be larger than the pooled sample unless the dimension of heterogeneity is relevant, i.e. there are indeed heterogeneous treatment effects. It is therefore reassuring that the standard errors in Figure 8 are similar in magnitude to those shown in Figures 7a and 7b.

Table A3 in the appendix reports the coefficients for both low- and high-capital utilization plants, ω_h and β_h^{3D} in (3), at the twelve-month horizon (OLS in column 1 and IV in column 2). Productivity increases following a demand shock in both high and low capital utilization plants, but the high utilization plants see 60% higher gains in labor productivity and double the TFP gains relative to low utilization plants. In evaluating this, one should note that even low utilization plants were operating at higher rates of capital utilization during the war than was common in peacetime, so that the heterogeneity is between plants with high and exceptionally high rates of utilization.

While demand shocks are identified through the instrument, capital utilization isn't randomly assigned.[53] We measure capital utilization at the onset of the war, which is less likely to confound productivity growth during the war and the triple differences specification in (3) absorbs differences in productivity *levels* in plants with different average capacity constraints through plant (by model) fixed effects. It is nevertheless possible that plants with greater initial capital utilization responded more to government purchases because of a different dimension of plant heterogeneity that was correlated with initial capital utilization.

Table A4 in the appendix compares plants with above and below median capital utilization (and labor market tightness). The first row shows labor productivity growth from 1943 to 1945. If anything, plants with initially low capital utilization rates saw greater productivity growth during the war, although the differences aren't statistically significant. The greater productivity growth of high-utilization plants seen in Figure 8 therefore reflects an increase in productivity *conditional* on a demand shock, not a general trend of faster productivity growth in those plants. There is also no statistically significant difference in firm age, the number of aircraft produced in January 1943, the initial level of productivity, the unit cost of aircraft, average aircraft wingspan, and the cumulative amount of public financing received during the war, when comparing plants with high and low initial capital utilization.[54]

One correlate with capital utilization does stand out: Plants with high capital utilization were older on average. This is in the context of a very young industry: the average plant was founded in 1934. But low capacity utilization plants were even younger and were founded in 1938, on average. Older plants had higher capital utilization early in the war because they were known entities and the first to receive orders. However, they had still not expanded their capacity to meet the wartime challenge. Capacity utilization could therefore merely capture plant age and it is plausible that young plants respond differently than old ones to demand shocks. However, most narratives go in the opposite direction: One might expect young plants to benefit more from demand, being

[53] Capacity utilization was indeed an important consideration in procurement decisions. See for example Fairchild & Grossman (1959) chapter VI.

[54] Plants in low wage counties received more public financing, but this goes in the wrong direction to explain the higher productivity growth of high-wage regions following a demand shock, which we will see shortly.

at a stage when they are bearing the initial fixed costs of production, still on the steep portion of their learning curve, and still familiarizing their customers (in this case the government) with their newer products (see Foster *et al.* 2016).[55]

Figure A.9 in the appendix investigates this confounding factor, repeating the triple-difference regressions, now controlling for plant age and the interaction between plant age (captured by a dummy equalling one if the plant is of above median age) and demand. This allows for the possibility that older plants, rather than plants with high utilization, saw greater responses of productivity growth to demand.[56] The figure shows slightly *larger* differences between high and low utilization plants when controlling for these additional terms, indicating that capital utilization, not plant age, is the relevant dimension of heterogeneity. Plant age itself slightly *decrease*s the impact of demand on productivity growth in this specification. Young plants appear to benefit more from increased demand as anticipated in the discussion above. This figure also includes productivity pre-trends and we see that high and low capital utilization plants follow parallel trends prior to the demand shock.

Investigating high pressure on labor, as opposed to capital, we use three metrics to evaluate labor shortages. Labor utilization is measured at the plant level as the average hours per worker in a plant. Local wages are another indicator of labor market pressures. Table A5 in the appendix shows that these various metrics of capital and labor shortages are correlated but these correlations aren't perfect. High wages could of course reflect high productivity rather than labor shortages. However, wages were regulated during the war and the government typically only approved wage increases when plants faced substantial labor shortages. This is evident from the last row of Table A5 in the appendix that shows a strong correlation between wages in 1942 and a dummy variable taking on a value of one if the plant was located in a county classified by the War Manpower Commission (WMC) as facing labor shortages.[57] Furthermore, the wage rate used is the average wage in the labor market *excluding* plants in the aviation industry. The third indicator is the WMC's classification of labor market tightness.

Figure A.10 in the appendix shows that plants with above-median hours per worker early in the war (January 1943, a month chosen to maximize coverage) saw relative increases in TFP when facing increased demand. Results are slightly stronger using local wages or WMC's classification early in the war to identify counties with labor shortages.

[55] This last factor is less relevant in the context studied here because these were young plants of established firms and were typically producing aircraft that were also being produced in other plants of the same, or another, firm.

[56] The cross-sectional distribution of plant ages is fully absorbed by production line fixed effects. The plant-age control is equivalent to controlling for plant-specific time trends.

[57] The WMC classified each labor market in the US into four categories 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.

Finally, Table A3 in the appendix shows several robustness exercises. The top panel of the table shows responses of output per hour worked at the twelve-month horizon following a shock to aircraft demand, and its interaction with a dummy variable equaling one if the plant had above median capital utilization at the beginning of the sample. The bottom panel shows similar responses for TFP. Columns 1 and 2 show OLS and IV regressions, corresponding to those seen in Figure 8. Column 3 a specification that replaces time fixed effects with time-by-region fixed effects. Column 4 reports a specification controlling for cumulative aircraft production. Column 5 controls for cumulative capital investment in machinery. Column 6 controls for plant age and the interaction between aircraft demand and a dummy equaling one if the plant is above median in age, as in Figure A.9. Column 7 reports a specification where observations are weighted by a production line's cumulative production over the course of the war.

Column 8 of the table interacts demand with capital utilization at the beginning of the war, instead of the dummy indicating whether the plant had above median capital utilization. That is, it replaces the discrete categories of capital utilization with a continuous interaction. The first row now 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. Results are both quantitatively and qualitatively similar to the discrete interaction specification. Column 9 interacts demand with a time-varying measure of capital utilization (12 month lagged) instead of initial capital utilization. Results are again similar, but need to be interpreted cautiously, because utilization may have varied across plants because of relative productivity dynamics. Column 10 then instruments this time varying measure of capital utilization with capital utilization at the beginning of the war.

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. This includes contemporaneous accounts, institutional histories of wartime agencies and military commands (cf. War Production Board 1945, US Civilian Production Administration 1947, and multiple volumes by each branch of the military), eye-witness accounts of key participants in the war production drive (cf. Nelson 1950, Janeway 1951, Jones & Angly 1951), and later histories (cf. Herman 2012, Klein 2013). Many of these accounts put emphasis on the mobilization of labor and capital, witnessed in Figure 2, but even contemporary observers pointed to increases in (total factor) productivity, beyond the accumulation of factors of production. Many explanations have been offered for this increase in TFP. I focus here on three explanations that appear to have the largest historical consensus, in that each is discussed as a potential contributor to the productivity surge in nearly every major historical work on the topic.

The first is the move from "job shop" production methods to "line" production methods. This explanation receives the greatest attention in historical analyses of the war production drive. In their seven volume history of the Army Air Forces in World War II, 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). 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.[58] Here is how Lilley *et al.* (1955) (p. 40-41)

[58] Indeed, they were often associated with hiring new middle management from the automotive industries. This resonates with the Acemoglu *et al.*'s (2020) finding that hiring innovative managers is associated with radical innovation

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 balancing 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.

It is difficult to verify these narratives empirically because there is no existing systematic account of production method improvements. In order to quantify their importance, I fill in this gap by cataloguing mass production methods in the World War II airframe industry. These new data are based on narrative accounts in contemporary newspaper articles and corporate annual reports.

My research team and I searched a variety of news sources for terms related to upgrades in production techniques. The search terms included the name of the aircraft firm (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). All relevant articles were then read by a research assistant 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.

The sources included the digital archives of main national (business) publications (New York Times, Wall Street Journal, Business Week, Fortune). Local newspapers were found through in-

in modern data.

ternet archival sources Chronicling America and Newspapers.com. Finally, we used Mergent Archives to search the annual reports of all aircraft companies for which such reports were available and included any self-reported moves to modern production line methods.

Figure A.11a in the appendix shows how new production methods were introduced over time according to our analysis of the sources. The figure shows the average count of mass production techniques introduced in aircraft plants and the share of aircraft plants reporting any mass production techniques up to that date. By the end of the war, nearly half of aircraft plants had modernized their production, with the average modernizing plant introducing 3 new production techniques.

The higher frequency methods used for the analysis of demand and productivity are less suited to analyze the evolution of methods. These are large changes in production that were stimulated because of past, current, or anticipated demand. Further, attempts to use time series methods as in the previous section leads to very inaccurate estimates because of the very low-frequency variation in the dependent variable, with plants making only few changes in production methods over the duration of the war.

Nevertheless, Figure 9 shows suggestive evidence that technology adoption was associated with both 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. It has the flavor of a conventional "learning by doing" regression, but with three important differences. First, the outcome variable is measured one year after the cumulative production variable, slightly mitigating the endogeneity concern. Second, the outcome variable is the adoption of new production methods rather than labor productivity. Finally, and important for the "learning by necessity" hypothesis, the sample in the scatter plot is separated between plants with initial capital utilization above and below the sample median.

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. A look at the upper right-hand quadrant of the plot shows that nearly all adopters had high rates of capital utilization. The association between experience and new production methods is economically significant, with a 10% increased production associated with the adoption of one new production method on average. In contrast, there is no association between production experience and technology adoption in low capital utilization plants. Cumulative production led to technology adoption primarily in "higher pressure" environments. This suggests that incentives mattered for technology adoption and productivity gains were associated with active managerial decisions to improve production methods rather than passive learning.

Outsourcing was a second 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."[59]

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.11b

[59] 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.*

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.

Formalizing this argument, Figure 10a shows how the percent of outsourced production responded to increased demand in the triple-difference LPIV specification of (3). It shows a temporary (roughly 1-year) but massive (10 percentage points of work-hours) increase in outsourced production following a 1 percent increase in aircraft demand (predicted by the leave-one-out instrument) in plants that were initially operating at high capital utilization relative to others. The reference plants with below-median capital utilization see a near zero response, so that the relative response plotted in 10a is also roughly the absolute response for high-utilization plants. High-pressure plants, but not others, used outsourcing as a way to circumvent tight capacity constraints and these plants saw not only effective capacity, but also greater TFP increases following demand shocks.[60]

While high-pressure plants used outsourcing to meet production demands, it doesn't necessarily follow that outsourcing increased productivity. There were some outsourcing skeptics at the time: "Some aircraft manufacturers remained skeptical as to the utility of subcontracting. They found it a singularly complex operation which sometimes placed a load on management as great or greater, it was argued, than that which it was supposed to relieve." (Craven & Cate 1955 p. 548). In their post-war post-mortem, Lilley *et al.* (1955) (p. 67) conclude:

> At first glance, subcontracting appeared to be a very attractive method of utilizing the long experience of nonaircraft companies in large-scale production while minimizing the disadvantage of their lack of technical know-how in the aircraft field... In actual experience, however, subcontracting was not so successful in relieving the management load o the old-line companies as might have been anticipated... Many of the executives interviewed expressed the view that subcontracting was more trouble that it was worth."

Lilley *et al.*'s (1955) main objections include the managerial burden of supervising feeder plants, particularly in face of frequent aircraft design changes and lower quality of production in feeder plants leading to many rejections and multiple inspections. It is hard to conceive of a compelling natural experiment to settle this dispute. Outsourcing was caused by increased demand and high pressure, which affected productivity through other channels.

[60] Productivity is measured through aircraft per hour, with hours including an estimate of the in-house hours saved due to subcontracting, so that there is no mechanical way in which outsourcing is associated with labor productivity. The data only provides measures of physical capital at the "mother plant". All results in the previous section are virtually unchanged when controlling for the share of outsourced production.

Relations between labor and management in munitions industries were extensively documented both during the war and in post-war histories. Many of these studies claim that improved labor relations–the third factor I investigate–was an important determinant of labor productivity. Economic theory has also emphasized the role of labor effort as a source of labor efficiency at business cycle frequencies. (Leibenstein 1966 refers to this as "X-efficiency" and Shapiro & Stiglitz 1984 and Yellen 1984 discuss pecuniary motivations to provide work effort.) 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.

Figure A.11c in the appendix corroborates these anecdotes. The median plant lost 5% of worker hours due to absenteeism at the beginning of the "year of production" of 1943 and around 7% by its end (with a spike to 9% in December 1943). Absence rates decline substantially through 1944, coming back down to 5% by 1945. 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.

The quote shows again how high demand provided incentive for managerial changes, in this case in labor relations. At low levels of demand, plants could combat absenteeism by hiring more workers. But at higher levels of demand, management had to confront the absenteeism problem itself.

Frequent turnover was also an impediment to production. Quit rates fluctuated substantially throughout the war and peaked at nearly 6% of the median plant (Figure A.11d). A report written by Douglas Aircraft management writes of the costs of turnover:[61]

[61] *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*.

> 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.

The quote illustrates how "learning by doing" (or forgetting) isn't merely passive. It is affected by management action to limit turnover and allow the "learning" to be retained. Aircraft manufacturers took a host of actions to tackle the absence and turnover crisis. Financial incentives were employed:

> The tens of thousands of workers in Grumman Aircraft Corp. plants on Long Island have proved conclusively that the Nation's manpower problems can be solved simply by working a little harder. With more pay as an incentive, Grumman in the past six months has increased production 40 per cent with fewer workers and at far less cost per plane. (Washington Evening Star, March 10, 1943)

But higher 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 checkups... 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)

Absence rates among women workers was nearly twice that of men. Many women entered the workforce for the first time during the war and faced a difficult balancing act without adequate childcare facilities. Many plants funded childcare facilities to ameliorate this problem. The mass migration into tight labor markets created a housing shortage. Management lobbied for new housing construction and payed for busses to transport workers to and from more distant places of residence.

There is no direct mechanical relationship between absence and productivity, because the latter is measured in aircraft per hour worked and doesn't include the hours lost to absence. Further, the historical discussion focuses on how absence limits production, not productivity. The effect of absenteeism on productivity is less straightforward. On one hand, worker absence could disrupt production, lowering remaining workers' productivity. On the other hand, absent workers may have otherwise been less productive than average ("negative selection"), so that their absence increases average productivity.

How might a demand shock affect quits and absence? If workers are averse to the pressures induced by higher demand, we'd expect these rates to increase following a demand shock. If instead, workers are intrinsically motivated, they might avoid missing work at periods of high pressure and we would see lower absenteeism following a demand shock. In fact, plants with low labor utilization see a 6% increase in absenteeism and a slight (but statistically insignificant) increase in the quit rate in the 6-months following a shock to demand. Figure 10 shows, however, that both absenteeism and turnover increased by *less* in high hour-per-worker plants. It repeats the triple-difference LPIV regression, with absence rates and quit rates as the outcome variables. Both rates decline in plants with (initially) high hours per worker upon receiving increased demand. The surprising result that labor problems increased less in these high pressured plants may indicate that management actions taken when the plant was under duress were enough to offset these pressures.[62]

We admittedly don't have a complete view of what plants did to increase productivity under pressures and multiple factors are likely in play. Rapid productivity growth when new production lines were initiated, and abundant testimony of observers, suggest that some form of institutional learning was important. Plants adopted new mass production methods when faced by new demands and/or hitting capacity constraints. The new methods will certainly have increased, and are correlated with, productivity growth. Pressured plants outsourced production to feeder plants. Finally, absenteeism and turnover are associated with lower productivity and there are indications that plants took action to curb labor dissatisfaction when problems came to a head.

Some productivity-enhancing measures explored here may have been transient. Outsourcing may be a temporary response to demand pressures and management may have reverted to previous labor relations when demand pressures subsided. On the other hand, historical narrative suggests that new production techniques adopted in the war were used and perfected in decades that followed. Unfortunately, the high-quality data collection efforts of wartime didn't continue into the post-war era and we are unable to verify the persistence of productivity gains.

Nevertheless, Table A6 in the appendix gives an indication that plants facing large demand

[62] An alternative explanation is that high hours per worker plants had more intrinsically-motivated workers, so that they are less inclined to shirk or quit when demand shocks hit.

pressures during the war continued to be more innovative in the post-war era. It plots the percent growth in patents from 1945 to 1955 on cumulative production during the war and its interaction with (an indicator of initially high) capital utilization. We see that plants with greater cumulative production during the war saw a surge in patenting in the decade following the war, but only if they operated at high levels of utilization. A ten percent increase in cumulative production is associated with 1.3% more patents (0.8% when patents are weighted by citations) for plants that operated under high utilization rates (compared to the low utilization plants).

6 Conclusion

A traditional view of the transmission of fiscal policy (and demand shocks more broadly) posits that increased demand increases output as firms soak up under-utilized employment or capital, from either within or outside the firm. The neoclassical view predicts that production will increase due to increased labor supply. Both theories would suggest that cyclical increases in demand can do little to expand output when the economy is at very high rates of utilization, nor can they affect productive capacity. Indeed, this was the common view at the onset of the Second World War, reflected in the "feasibility dispute," where economists warned that the economy could not sustain the planned war production drive, while the military insisted that it must.

This paper sheds new light by showing that slack does indeed play an important role in plants' responses to increased public demand. Bringing evidence from the Second World War, we see that plants with rates of capacity utilization that would normally be viewed as "overheating" met the production challenge through productivity increases. 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, the largest shock to public spending in US history. Can an episode so distant in history have implications to the modern economy? Of greatest concern is whether the wartime price and wage controls dampened inflationary pressures that would appear in a similar peacetime setting. The aircraft industry was in fact exempt from price controls during the war. Nevertheless, the price of aircraft *declined* dramatically during the war, indicating that productivity gains were more than sufficient to counteract inflationary pressures due to high demand. Further, the mechanisms through which plants confronted high demand are available to plants in peacetime and imply that the aggregate supply curve isn't entirely vertical, even at high utilization rates. While demand pressures no doubt leads to inflation, this study suggests a silver lining. Businesses that are strained may find ways to enhance productivity when facing exceptional demand. Nevertheless, the question merits further investigation in peacetime to see how valid the results remain in other settings.

While world wars will hopefully remain a rarity, there are lessons from wartime in the age of Covid-19 and the war in Eastern Europe. The pandemic has affected different sectors of the economy differently, with some showing substantial excess capacity and shortages arising in others. Geopolitical risks and sanctions put a different set of supply constraints on firms worldwide. While such constraints are real and 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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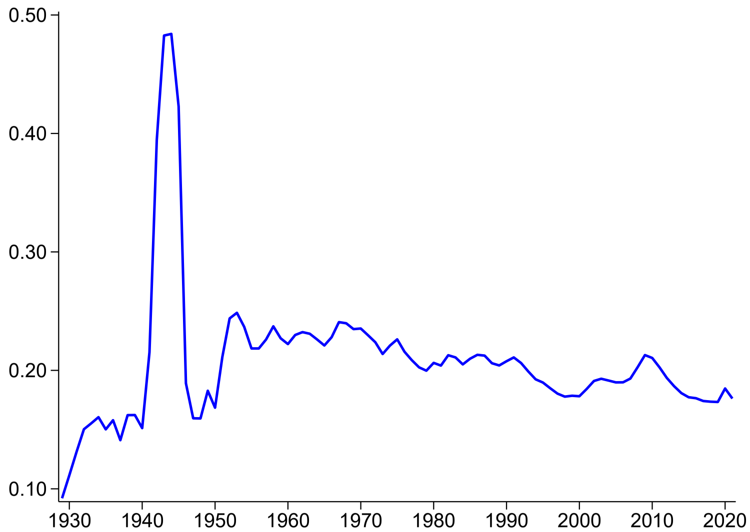
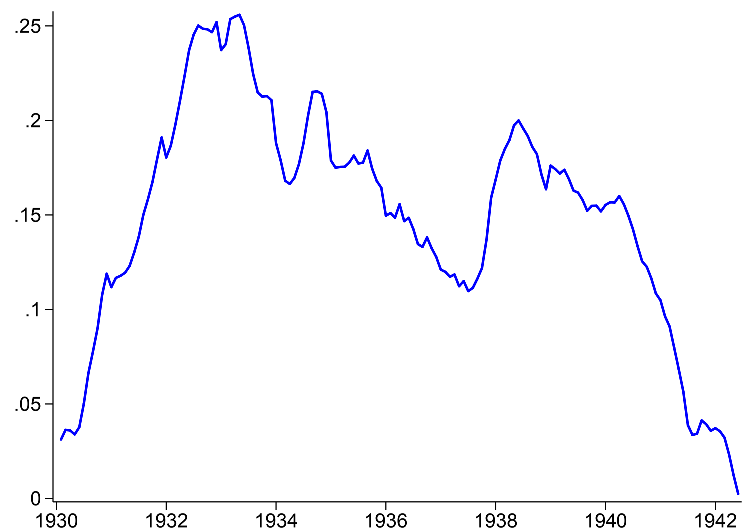
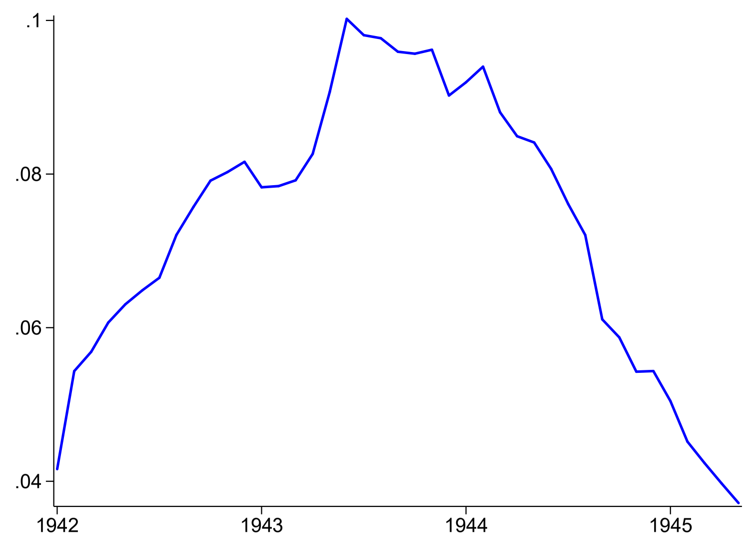
Figure 1: Government Spending, Unemployment, and Aircraft Procurement in the Second World War



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



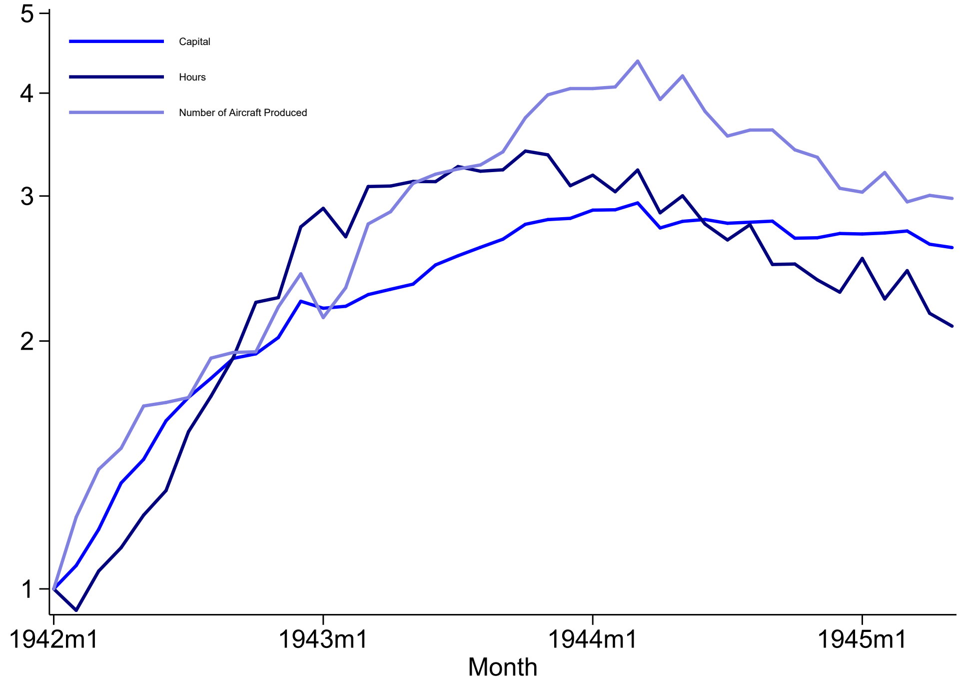
(b) Unemployment



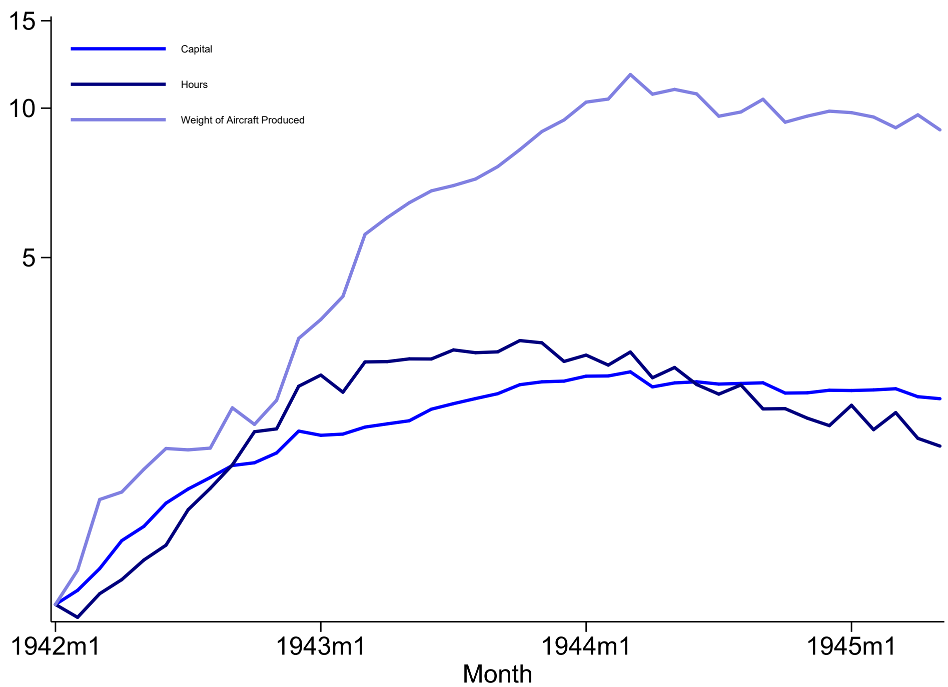
(c) Aircraft Procurement, percent of 1939 GDP

Note: Panel (a) shows government consumption expenditure and gross investment as a percent of GDP in the US since 1929. Source: Bureau of Economic Analysis and the author. Panel (b) shows the US unemployment rate from the great depression to the US's formal entry into the Second World War. Source: NBER Macrohistory Database. Panel (c) shows annualized government aircraft procurement as a percent of pre-war (1939) GDP. Source: War Production Board Listing of Major War Supply Contracts, BEA, and the author.

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



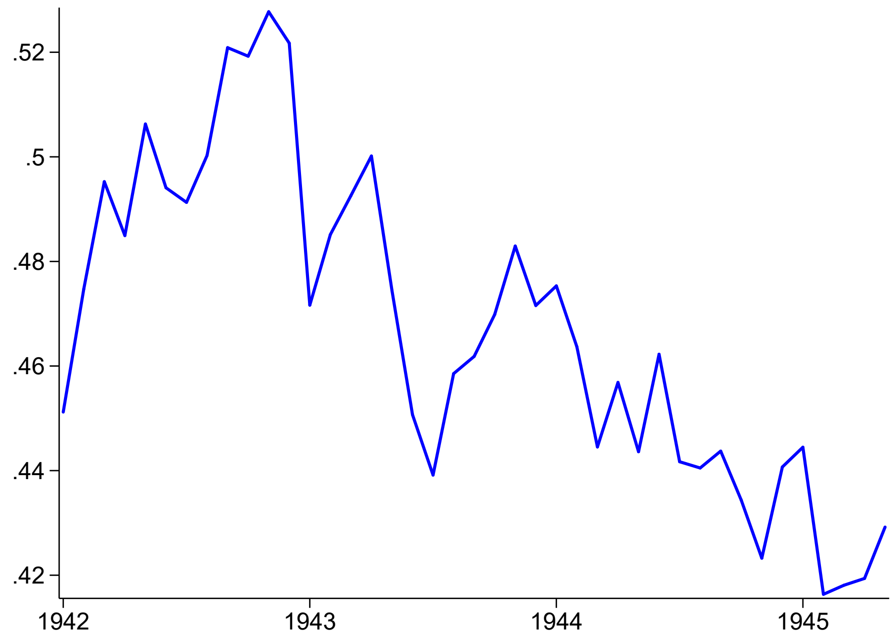
(a) Capital, Labor, and Number of Aircraft Produced, Indexes



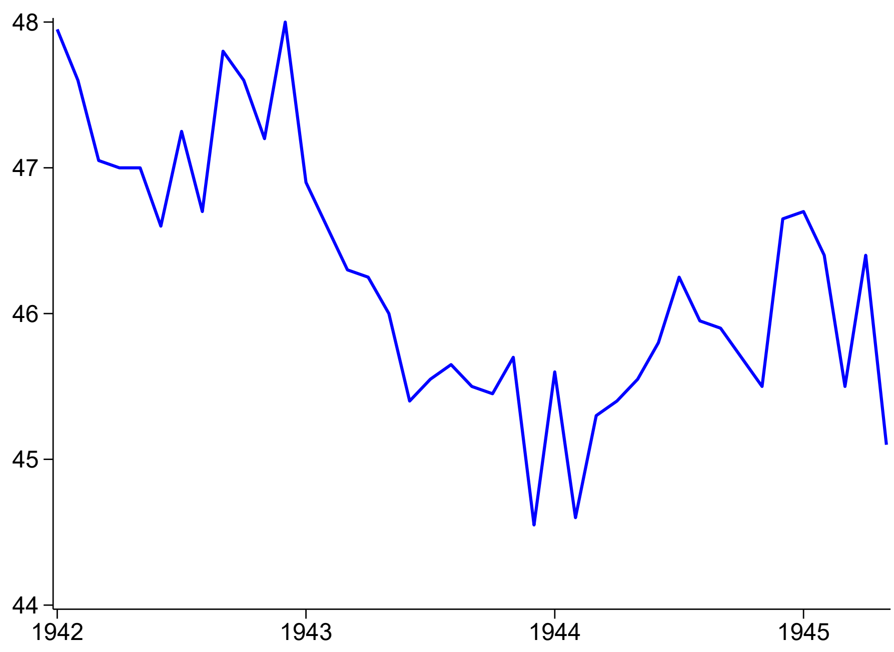
(b) Capital, Labor, and Weight of Aircraft Produced, Indexes

Note: The figures show aggregate inputs to and outputs of production in the airframe industry. 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: AMPR and the author.

Figure 3: Capital and Labor Utilization in Airframe Plants



(a) Capital (Shift) Utilization

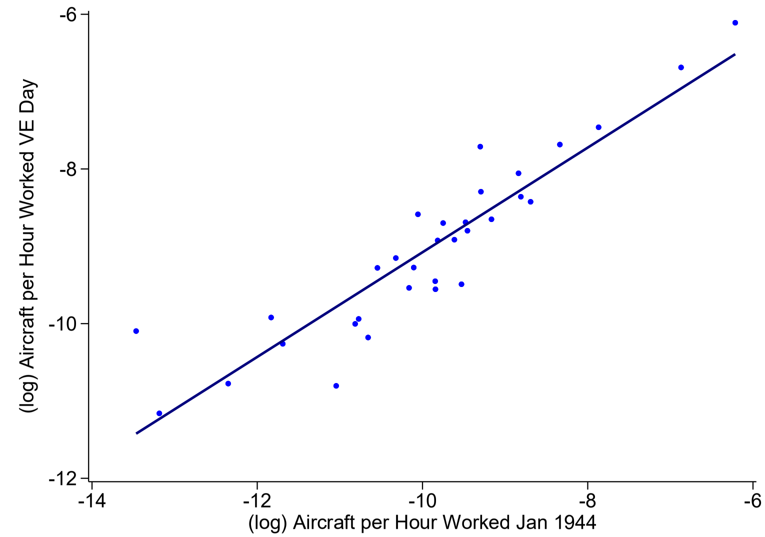


(b) Hours per Worker

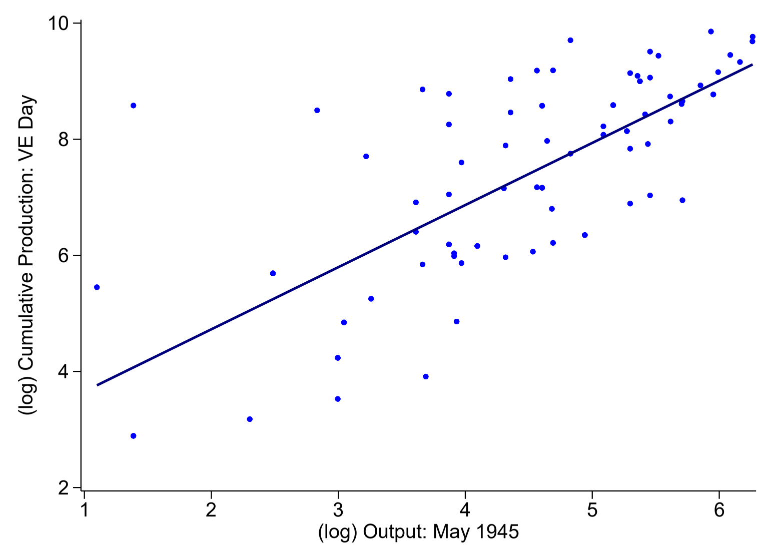
Note: Panel (a) shows shift utilization for the median airframe plant, estimated as described in Section 2. Panel (b) shows hours per worker in the median airframe plant. Source: AMPR and the author.

Figure 4: Autocorrelation in Output And Productivity

(a) Past Productivity and Subsequent Cumulative Production



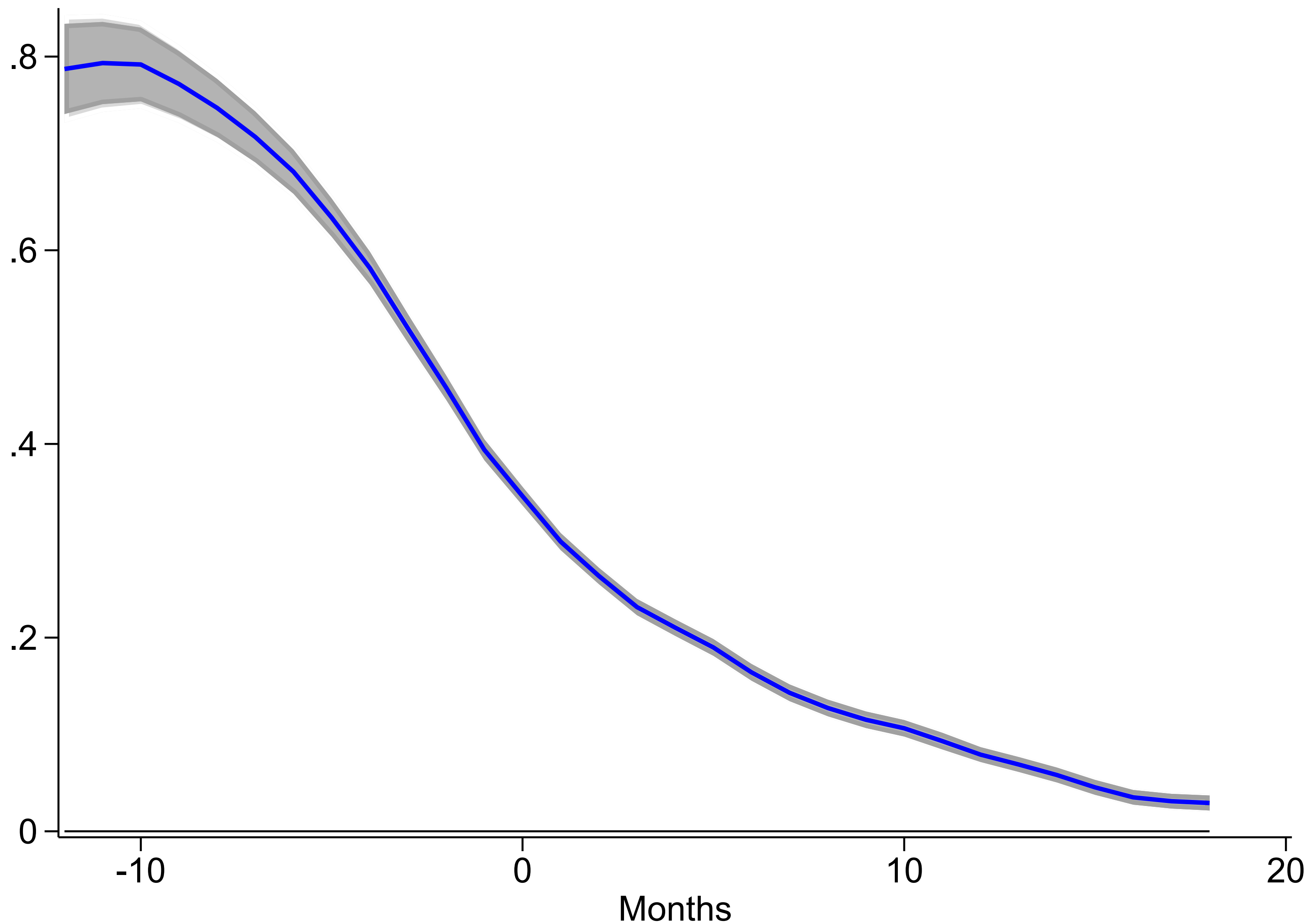
(b) Past and Current Productivity



(c) Cumulative and Current Production

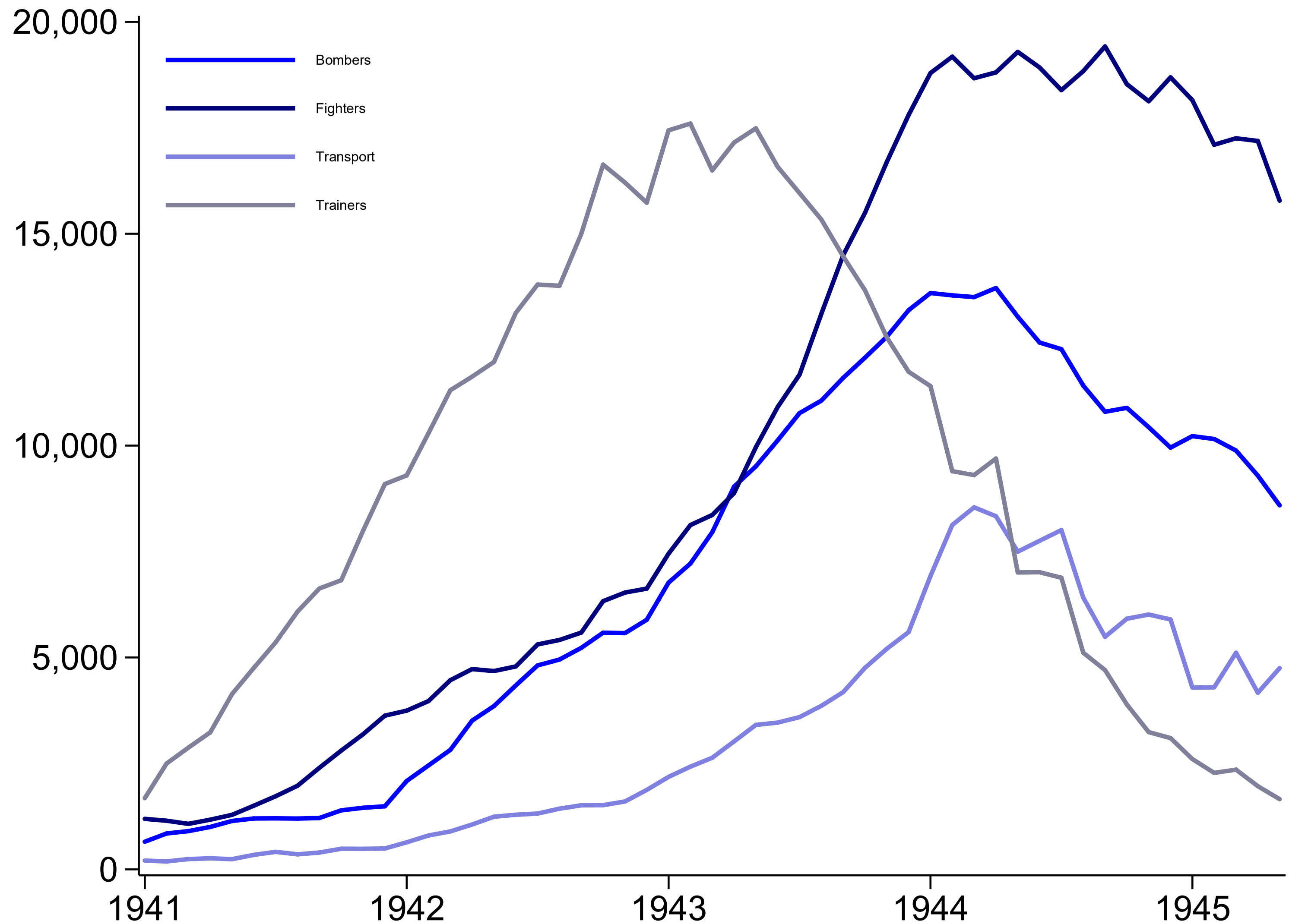
Note: The figure shows scatter plots at the plant-by-aircraft model level. Panel (a) gives (log) cumulative production up to May 1945 (VE-day) against (log) aircraft per hour worked in January 1944, showing that *past* productivity is correlated with later cumulative production. Panel (b) gives (log) aircraft per hour worked in May 1945 against (log) aircraft per hour worked in January 1944, showing strong autocorrelation in productivity. Combined, these two panels show that past productivity is confounding the correlation between current productivity and cumulative production, often viewed as an indication of learning by doing. Panel (c) gives cumulative production up to May 1945 against production in the single month of May 1945, showing the strong strong autocorrelation of production. This last panel illustrates the challenge in disentangling the effects of current output (scale effects) and cumulative output (experience or learning effects)

Figure 5: Dynamic Response and Pre-Trend of Labor Productivity in a Traditional Learning By Doing Regression



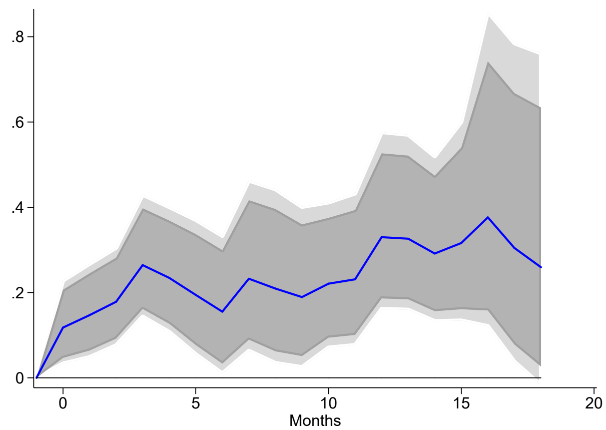
Note: The figure shows the response of (log) aircraft per hours worked at time $t + h$ to (log) cumulative aircraft produced at time $t = 0$, with the x-axis giving the horizon h. The shaded areas show 95% Newey-West confidence intervals. Traditional LBD regressions report the coefficient of $h = 0$,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

Figure 6: Aircraft Production per Production Line by Broad Aircraft Type

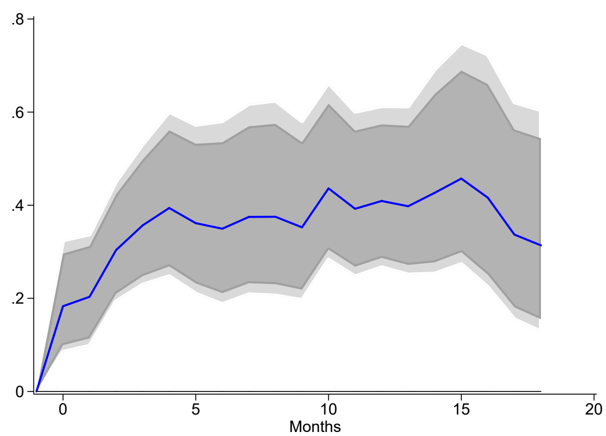


Note: The figure illustrates the instrument described in Section 3 and summarized in equations (1) and (2). It shows monthly aircraft production in the average production line producing fighters, bombers, transport aircraft, and trainers (listed from darkest to lightest shaded lines). Differential demand 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 int 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.

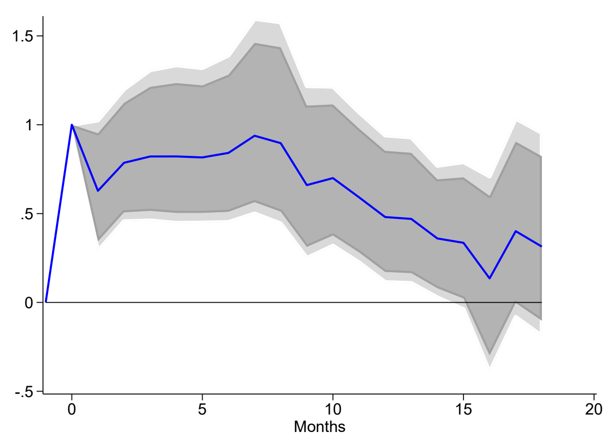
Figure 7: Responses to a 1% Shock to Aircraft Demand



(a) log Aircraft per Hour Worked



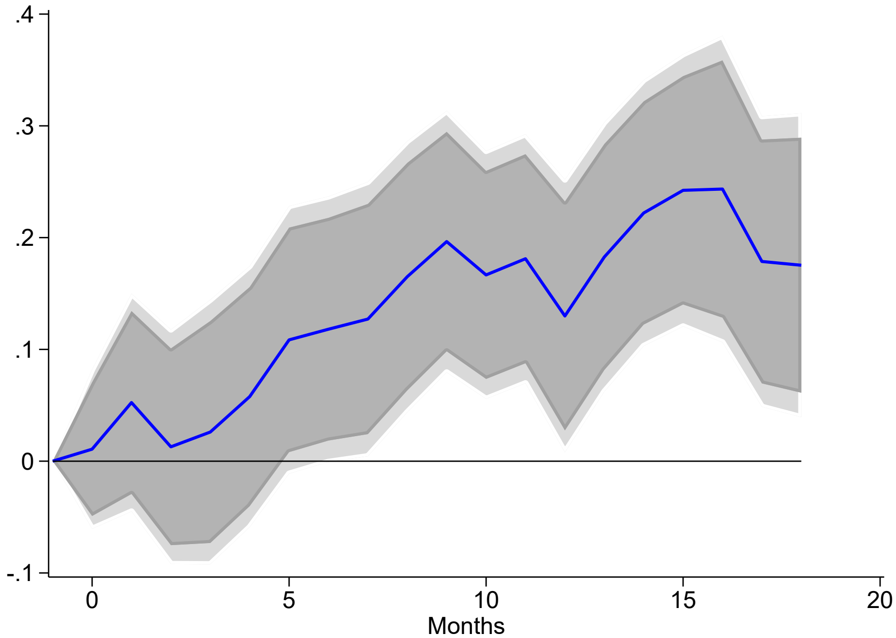
(b) TFP (capital utilization adjusted)



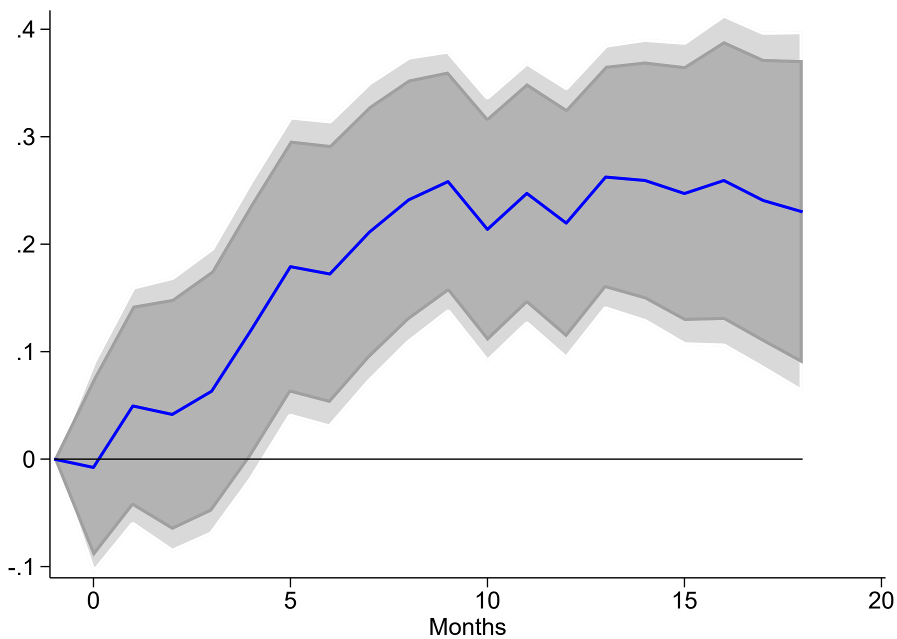
(c) log Aircraft Produced

Note: The figure shows the response of (log) aircraft per hour worked (panel a), TFP (capital utilization adjusted, panel b), and production (panel c) to a one percent shock to aircraft demand. The shaded areas show 90% and 95% Finlay & Magnusson (2009) weak-instrument robust confidence intervals. Estimates are based on local projections, with aircraft demand instrumented with the instrument described in Section 3, and laid out in equations (1) and (2). First stage Montiel Olea & Pflueger (2013) F-statistic at 12-month horizon = 30, 54, and 34 in the three panels.

Figure 8: Response of Output per Hour Worked and TFP to a 1% Shock to Aircraft Demand in High Capital Utilization Plants (relative to Low)



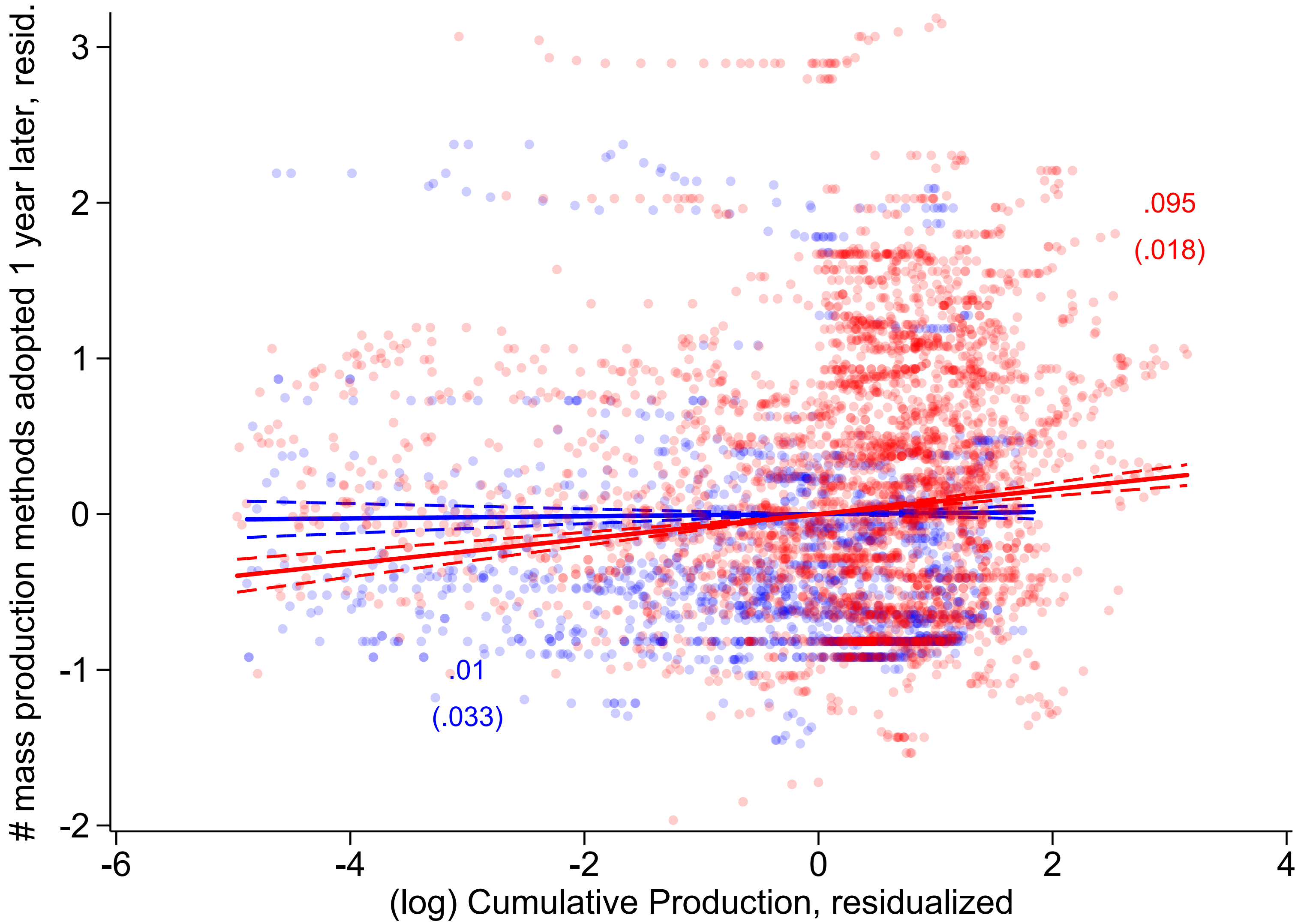
(a) Output per Hour Worked



(b) TFP

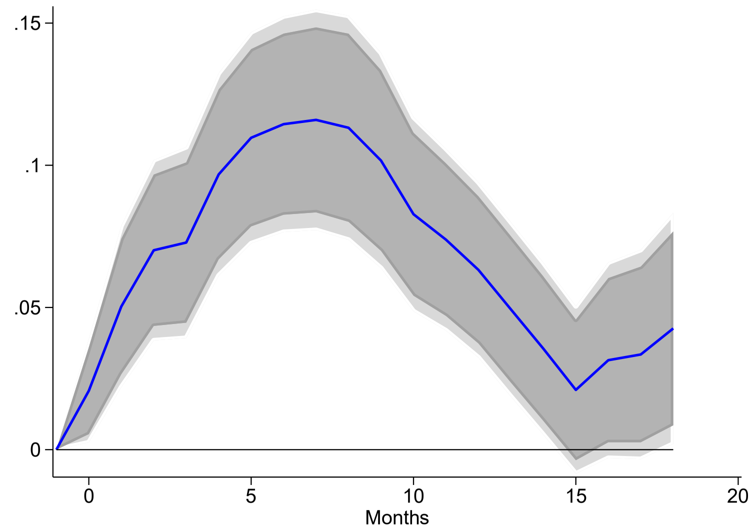
Note: The panels show responses of (a) (log) aircraft per hour worked and (b) TFP to 1% shocks to aircraft demand at month zero in plants with above median initial capital utilization relative to those with below median utilization. The shaded areas show 90% and 95% Finlay & Magnusson (2009) weak-instrument robust confidence intervals. Estimates are based on local projections, with aircraft demand and its its interaction with initial capacity utilization jointly instrumented by the instrument described in Section 3 and its interaction initial capacity utilization. The specification includes month and plant-by-model fixed effects. First stage F-statistic at 12-month horizon = 16 and 27 in the top and bottom panels, respectively.

Figure 9: Adoption of Mass-Production Methods by Cumulative Production and Capital Utilization

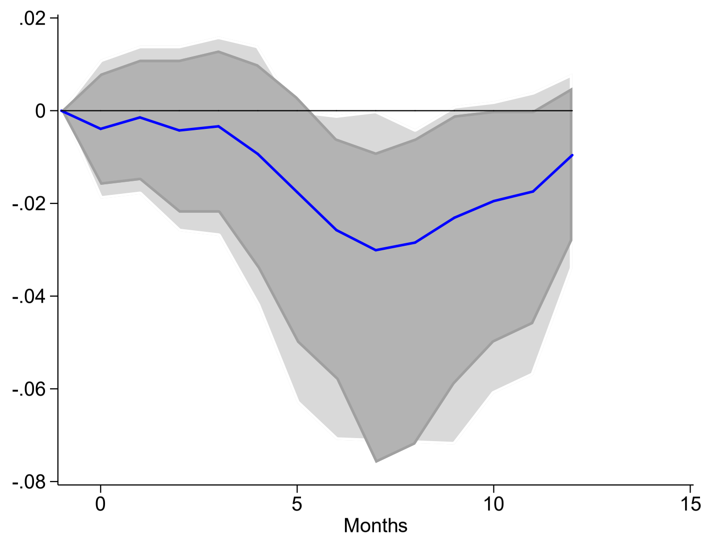


Note: The figure show the number of mass production methods adopted (with a one-year lag) against the (log of) cumulative production in a production line. Both variables are residualized from monthly, plant, and aircraft model fixed effects. Red dots represent plants that had above median capital utilization at the beginning of the war and blue dots represent plants with below median capital utilization. Fitted regression lines for the two sub-samples 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.

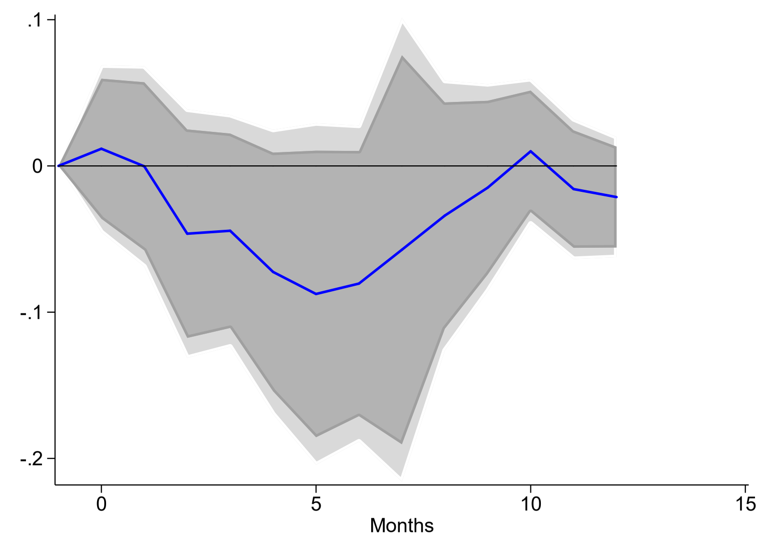
Figure 10: Responses to a 1% Shock to Aircraft Demand in High Utilization Plants (relative to Low)



(a) Outsourcing



(b) Absence Rate

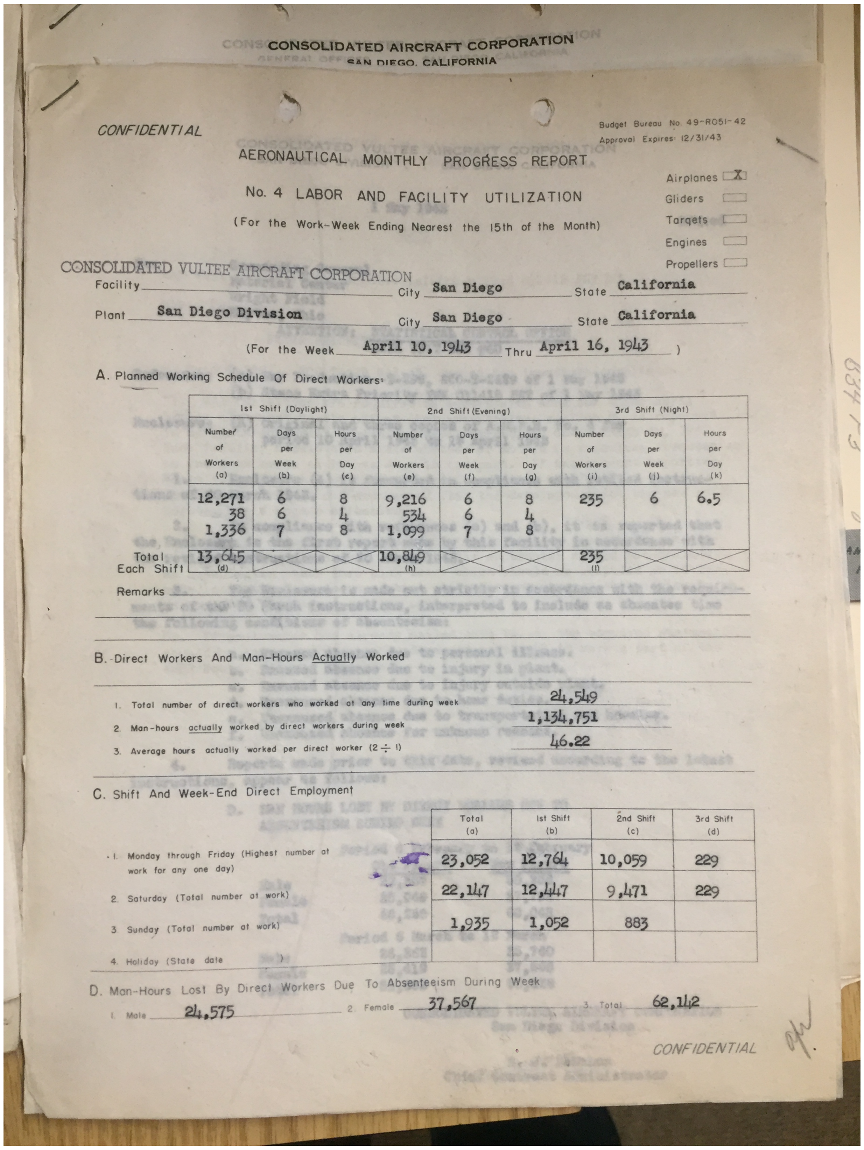


(c) Quit Rate

Note: The panels show responses of variables to 1% shocks to aircraft demand at month zero in plants with above median initial capital or labor utilization relative to those with below median 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 percent of hours lost to absenteeism and panel (c) the response of the percent of the workforce quitting each month, both in high vs. low (initial) hours per worker plants. The shaded areas show 90% and 95% Finlay & Magnusson (2009) weak-instrument robust confidence intervals. Estimates are based on local projections, with aircraft demand and its its interaction with initial capacity utilization or hours per worker jointly instrumented by the instrument described in Section 3 and its interaction initial capacity utilization or hours per worker. First stage F-statistic at 12-month horizon = 19 , 6, and 2 in panels a to c, respectively.

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 [ ]

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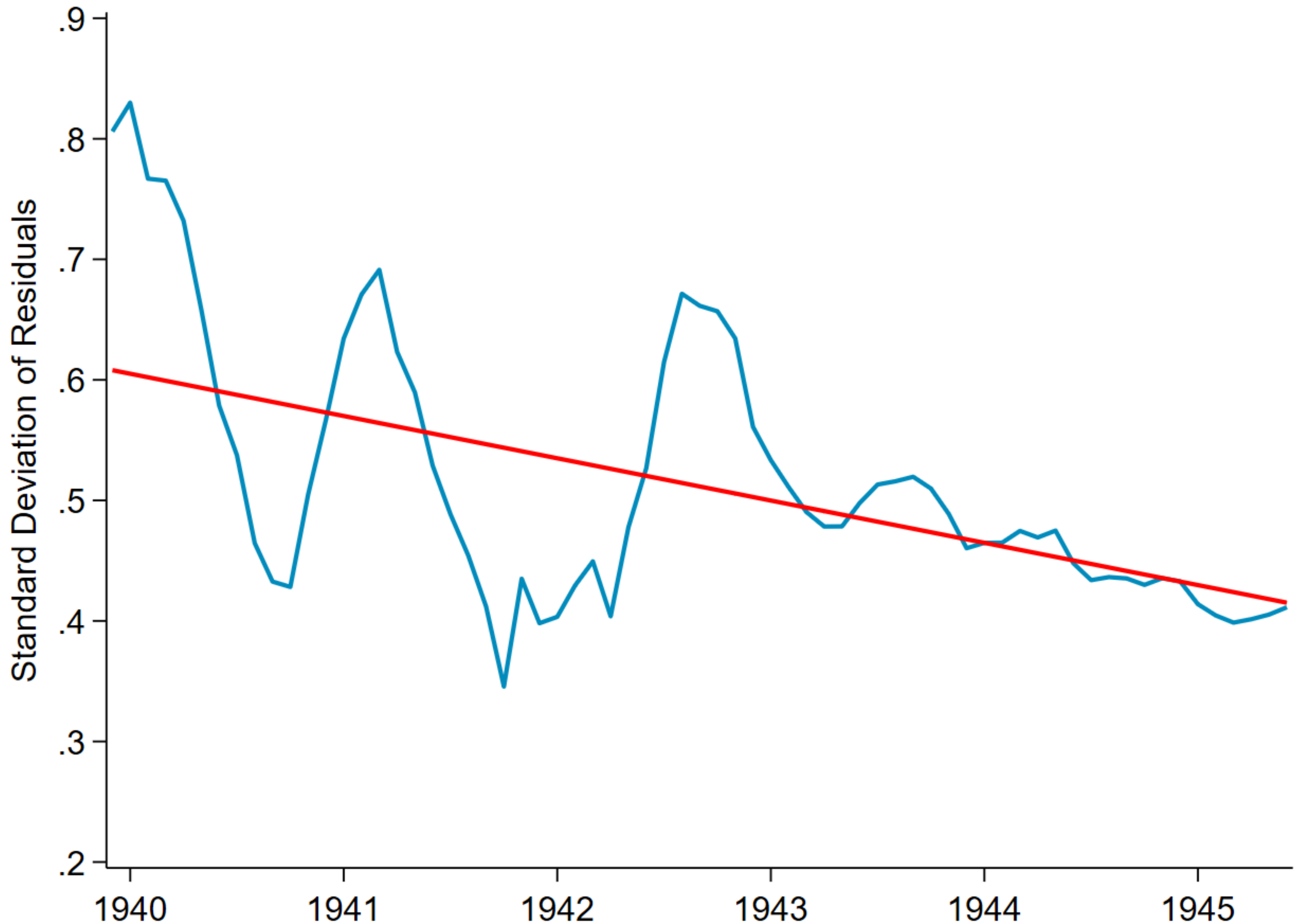
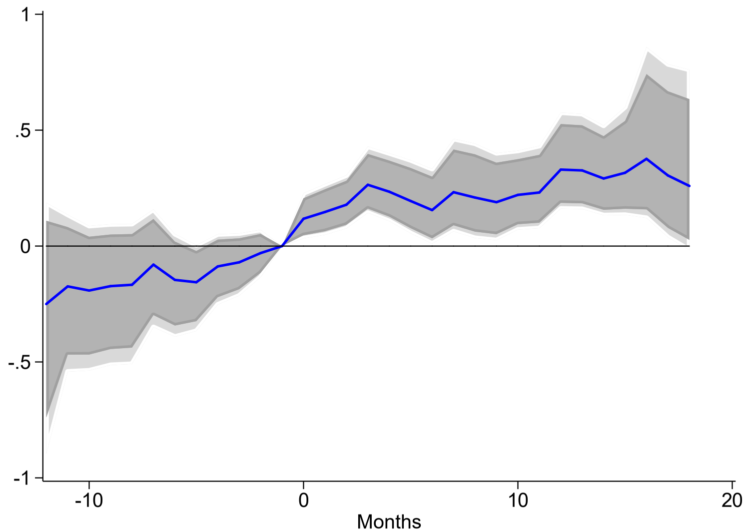
Note: Sample page from Aeronautical Monthly Progress Report (AMPR) form filled out by Consolidated Vultee Aircraft Corporation, San Diego, in April 1943. This was a standardized form filled out by all aircraft manufacturers during the war. The sample comes from AMPR No. 4, which gives details on shift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

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

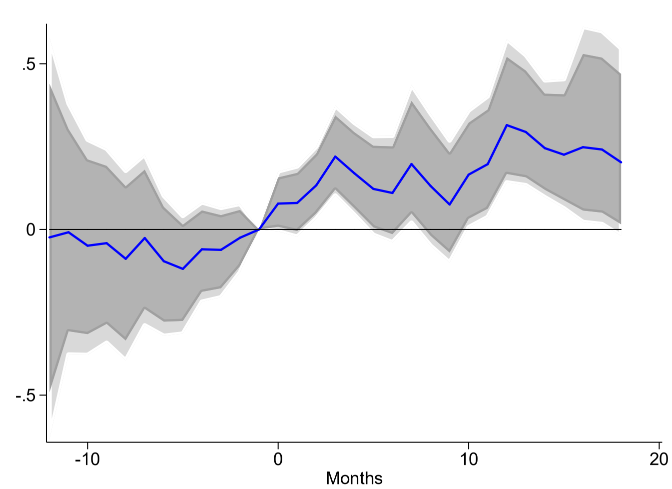


Note: The figure shows the standard deviation of log aircraft per hour worked (labor productivity) across airframe manufacturers in each month, 5-month moving average. Labor productivity is residualized from time fixed and aircraft model fixed effects. The model fixed effects are crucial to absorb differences 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.

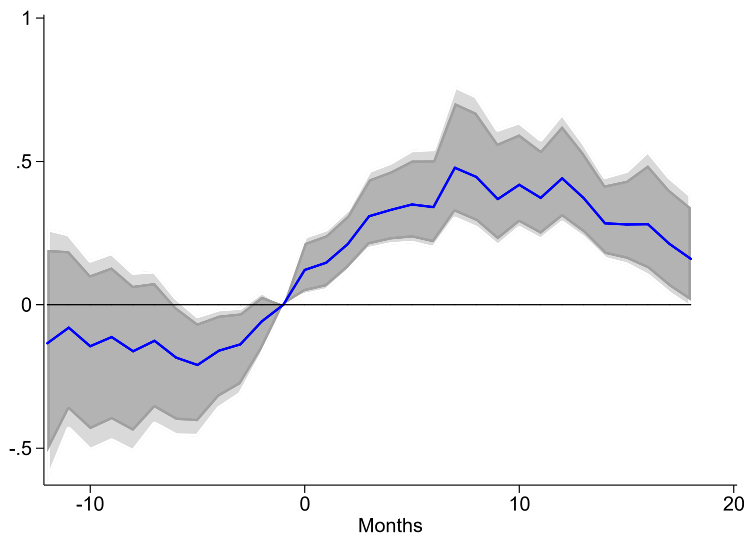
Figure A.3: Pre-trends in Labor Productivity and TFP



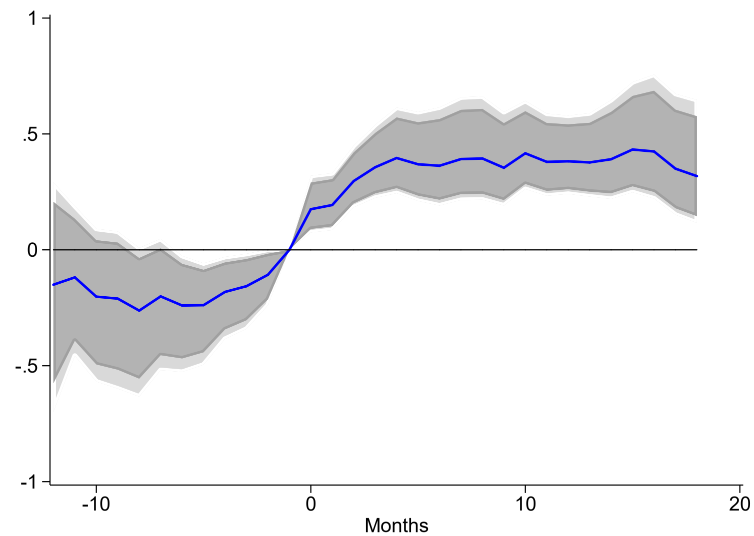
(a) Output per Hour Worked



(b) Output per Hour Worked



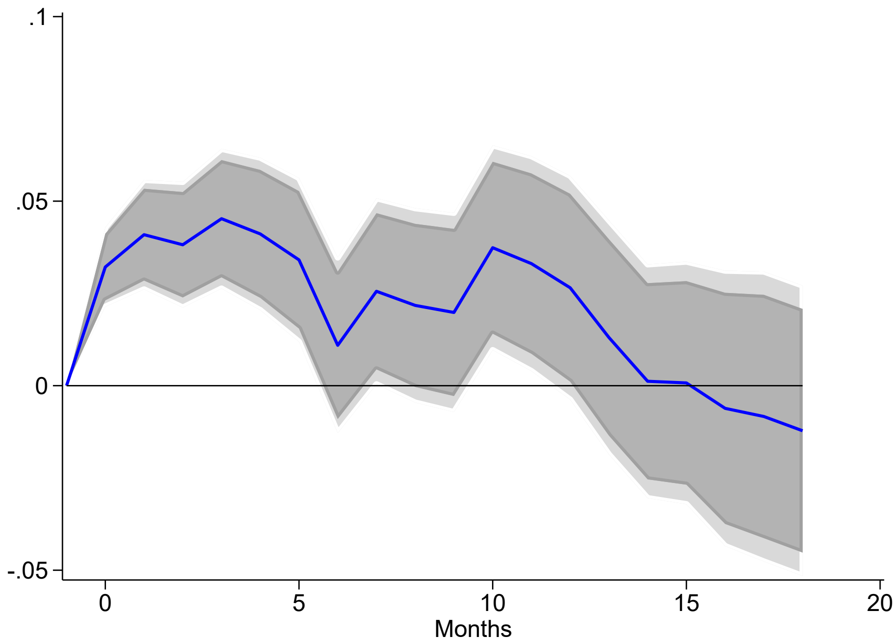
(c) Output per Hour Worked



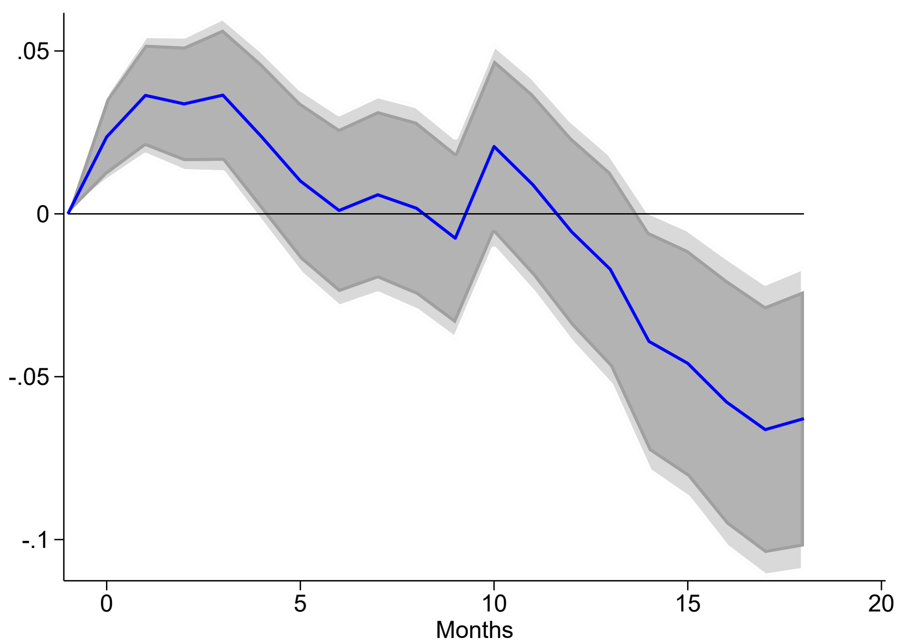
(d) TFP

Note: The panels show responses of labor productivity (panels a to c) and TFP (panel d) to 1% shocks to aircraft demand at month zero.The shaded areas show 90% and 95% Finlay & Magnusson (2009) weak-instrument robust confidence intervals. Estimates are based on local projections, with aircraft demand instrumented with the instrument described in Section 3, and laid out in equations (1) and (2). Panel (b) replaces time fixed effects with time-by-region fixed effects and panel (c) returns to nationwide time fixed effects and controls for six lags of the capita to labor ratio. First stage Montiel Olea & Pflueger (2013) F-statistics at 12-month horizon = 30, 23, 42 and 54, respectively. 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.4: Response of Output per Hour Worked to a 1% Shock to Aircraft Demand (OLS)



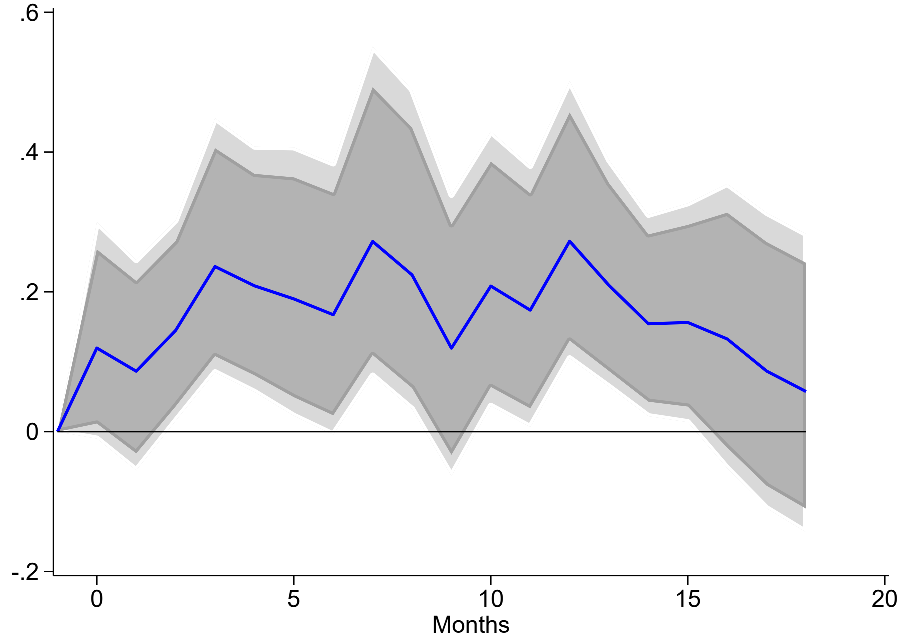
(a) Output per Hour Worked



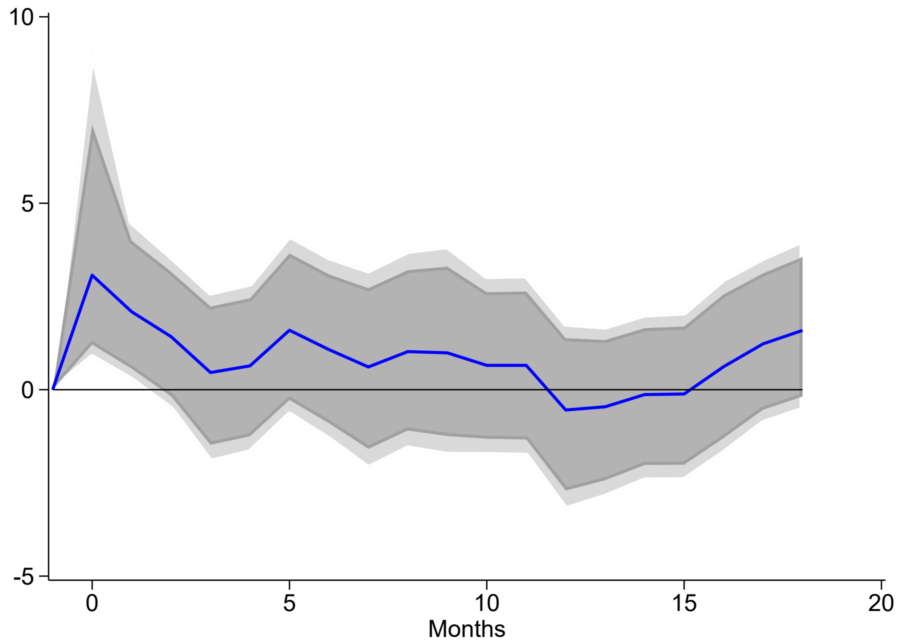
(b) TFP

Note: The panels show responses of (a) labor productivity and (b) TFP to 1% shocks to aircraft demand at month zero. The shaded areas shows 90% and 95% Newey-West confidence intervals. Estimates are based on OLS local projections, as in (2).

Figure A.5: Learning vs. Current Demand



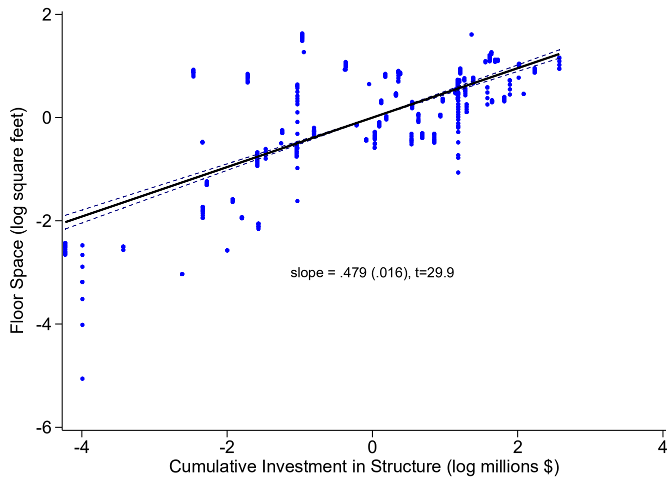
(a) Response to Demand, Controlling for Cumulative Output (Experience)



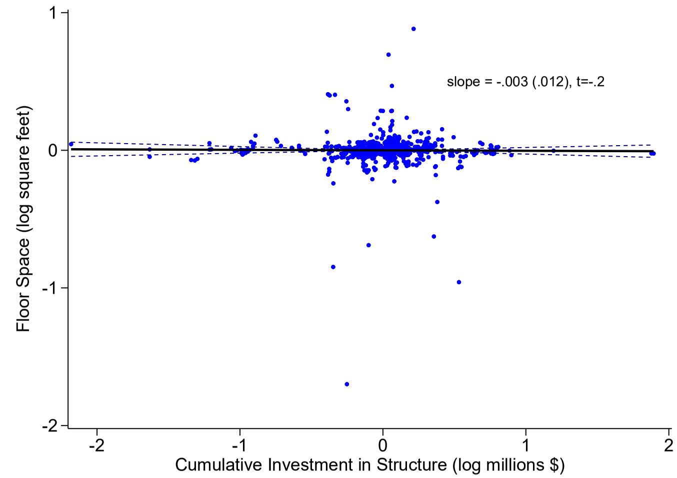
(b) Response to Experience, Controlling for Current Production

Note: Panel (a) shows the response of (log) aircraft per hour worked to a one percent shock to aircraft demand, with aircraft demand instrumented by the instrument described in Section 3, and laid out in equations (1) and (2). The regression includes a control for cumulative production in production line $\text{Experience}_{mpt} = \log\left(\Sigma_{s=0}^{t}\exp(D_{mpt})\right)$. First stage F-statistic at 12-month horizon = 33. Panel (b) shows the response of (log) aircraft per hour worked to a one percent shock to Experience_{mpt}, with this variable instrumented by the equivalently constructed cumulative instrument as in (1). First stage F-statistic at 12-month horizon = 24. The shaded areas show 90% and 95% Finlay & Magnusson (2009) weak-instrument robust confidence intervals.

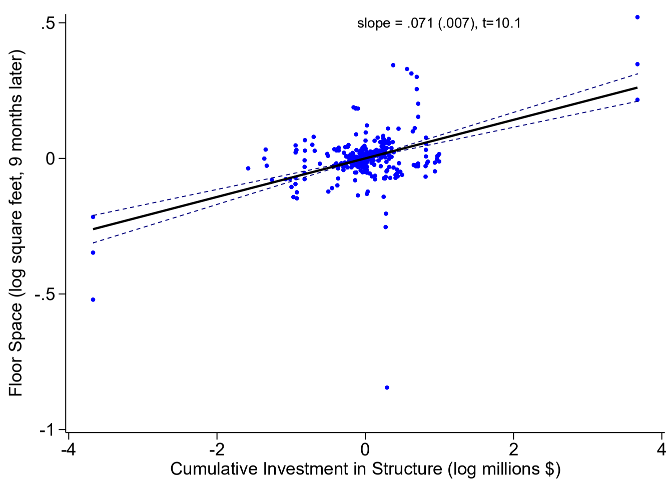
Figure A.6: Comparing Measures of Plant Capital



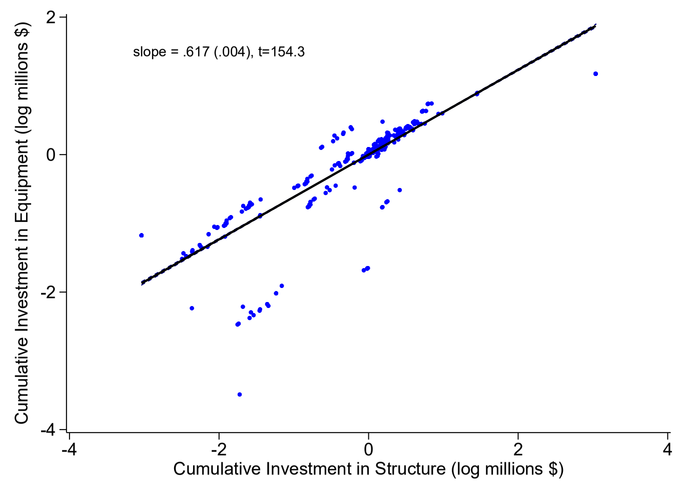
(a) Floor Space vs. Capital Investment in Structures



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



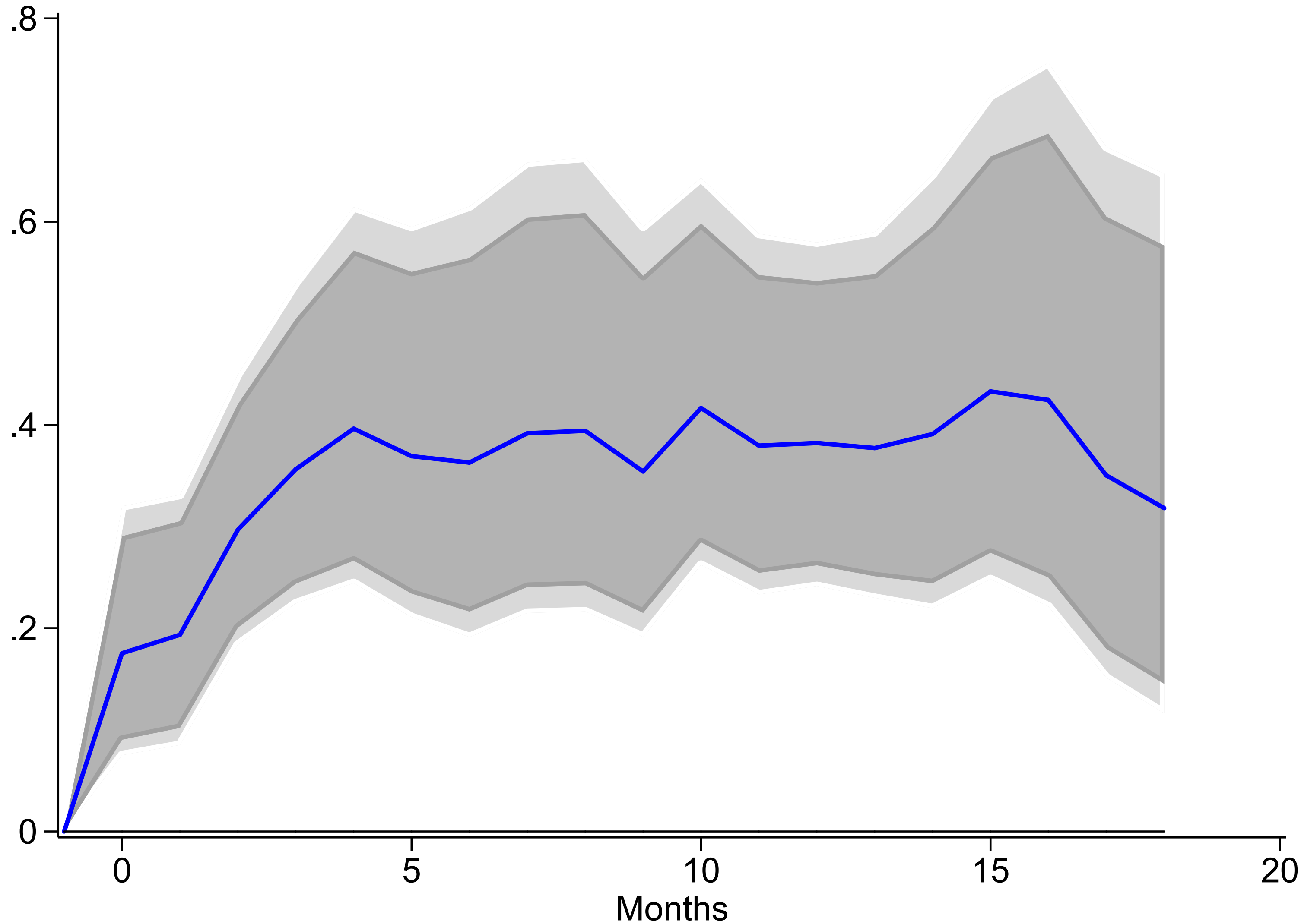
(c) Floor Space with 9 month lag vs. Capital Investment in Structures with 2 way fixed effects



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

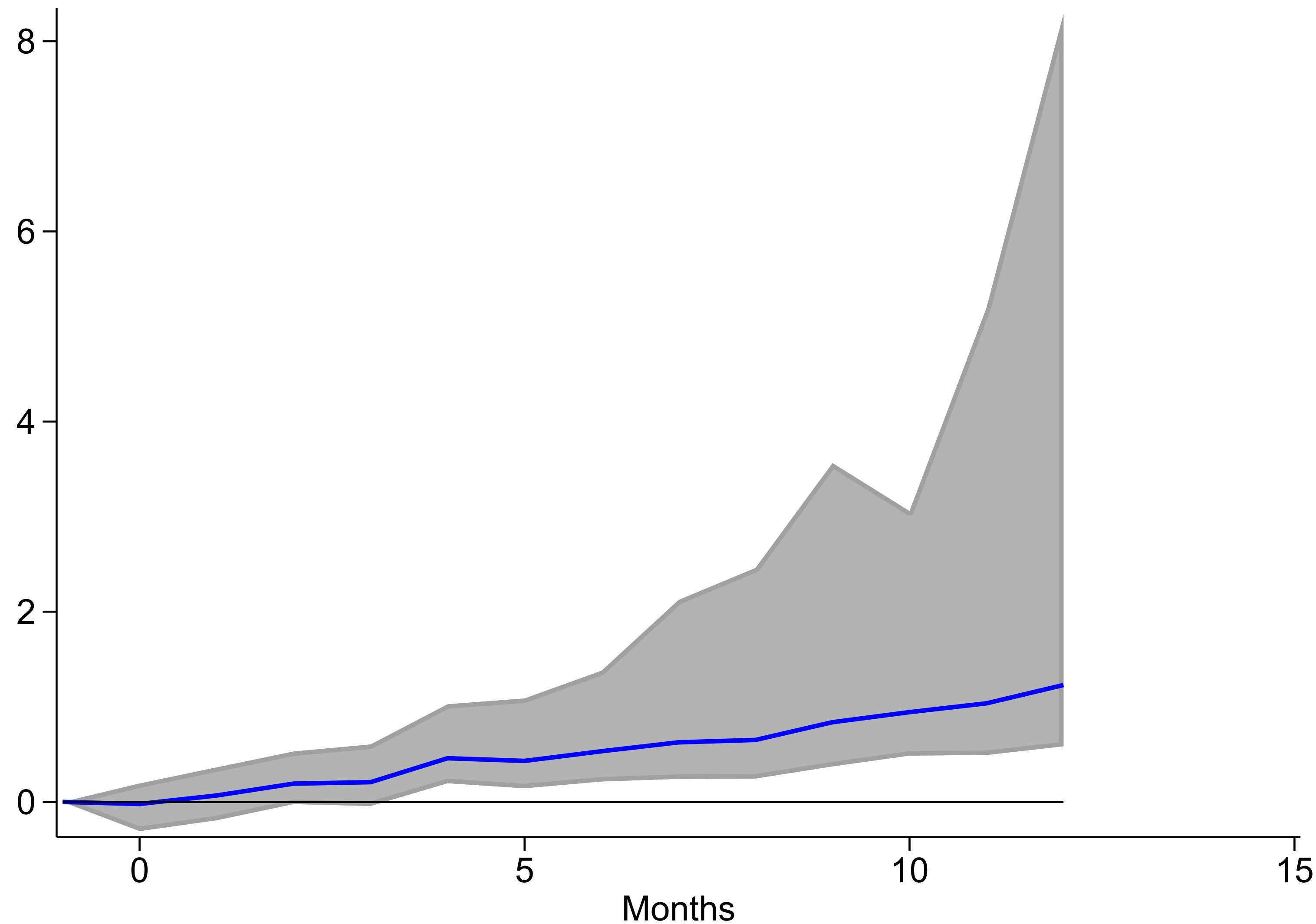
Note: Panel (a) shows a scatter plot of floor space in (log) square feet and cumulative investment in structures in (log) millions of US$. Each observation is a monthly reading of two variables for a specific plant. Panel (b) shows the same figure residualized from monthly and plant fixed effects. The zero correlation in panel (b) means that the raw correlation in panel (a) is driven by plants having different amounts of both investment in structures and floor space throughout the war and by the increase 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.

Figure A.7: Response of TFP (not adjusted for Capital Utilization) to a 1% Shock to Aircraft Demand



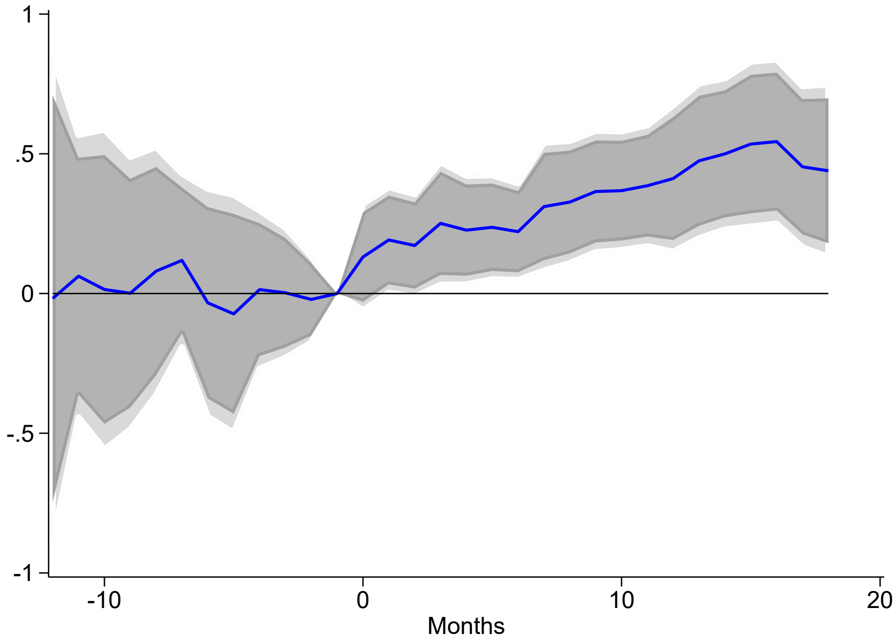
Note: The figure shows the response of TFP to a one percent shock to aircraft demand. The shaded area shows 90% Finlay & Magnusson (2009) weak-instrument robust confidence intervals. Estimates are based on local projections, with aircraft demand instrumented with the instrument described in Section 3, and laid out in equations (1) and (2). First stage Montiel Olea & Pflueger (2013) F-statistic at 12-month horizon = 52.

Figure A.8: Response of TFP to a 1% Shock to Aircraft Demand, Using Demand Shocks Only from First Half of Sample

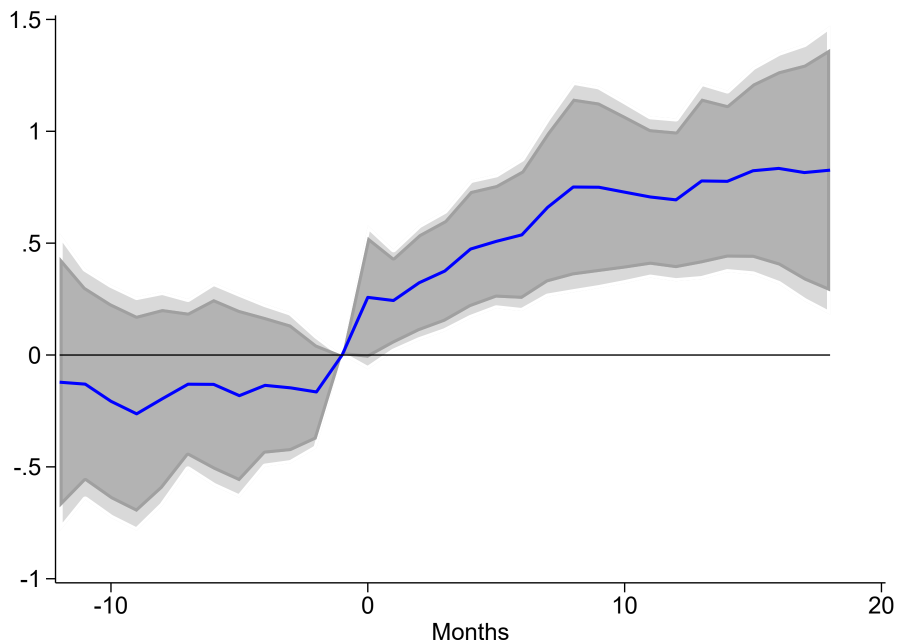


Note: The figure shows the response of TFP to a one percent shock to aircraft demand. The shaded areas show 90% and 95% Finlay & Magnusson (2009) weak-instrument robust confidence intervals. Estimates are based on local projections, with aircraft demand instrumented with the instrument described in Section 3, and laid out in equations (1) and (2). 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). First stage Montiel Olea & Pflueger (2013) F-statistic at 5-month horizon = 9, at 10-month horizon = 5.

Figure A.9: Response of Productivity to a 1% Shock to Aircraft Demand in high vs. low capital utilization plants: Controlling for Plant Age



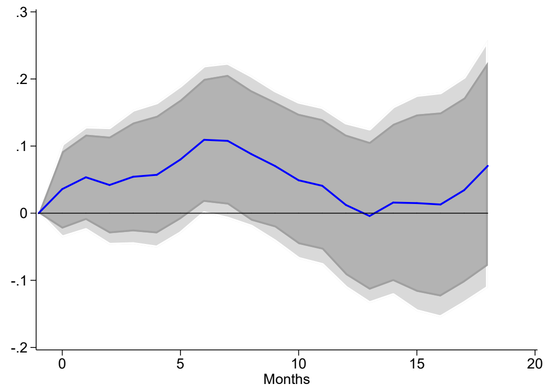
(a) Output per Hour Worked



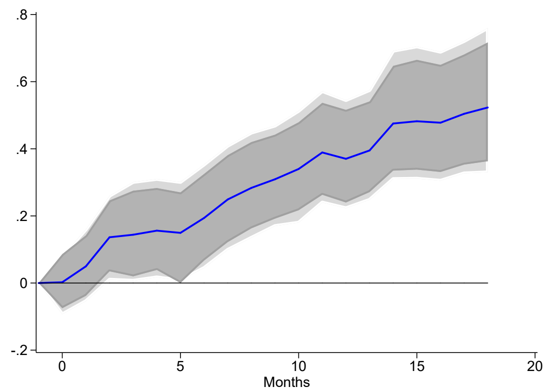
(b) TFP

Note: The panels show responses of (a) (log) aircraft per hour worked and (b) TFP to 1% shocks to aircraft demand at month zero in plants with above median initial capital utilization relative to those with below median utilization. The shaded areas show 90% and 95% Finlay & Magnusson (2009) weak-instrument robust confidence intervals. Estimates are based on local projections, with aircraft demand and its its interaction with initial capacity utilization jointly instrumented by the instrument described in Section 3 and its interaction initial capacity utilization. The specification includes month and plant-by-model fixed effects and controls for plant age and the interaction between demand and a dummy equaling one if the plant was above median in age in January 1943. Negative horizons are before the shock to demand and show pre-trends, evaluating differential trends of plants receiving a demand shock at time zero. First stage F-statistic at 12-month horizon = 6 and 7 in the top and bottom panels, respectively.

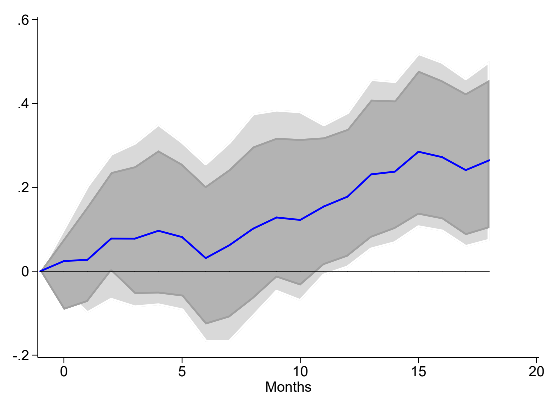
Figure A.10: Response of TFP to 1% Aircraft Demand Shock in Tight vs. Looser Labor Conditions



(a) Heterogeneity Based on Hours per Worker



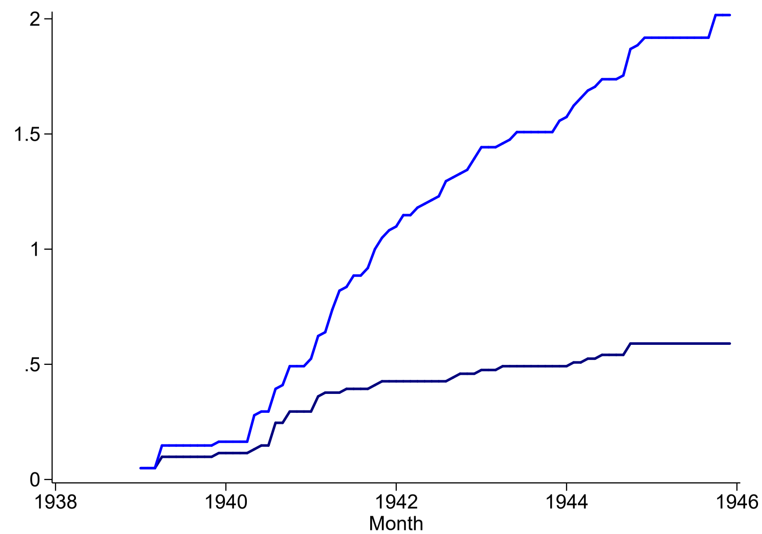
(b) Heterogeneity Based on Local Wages



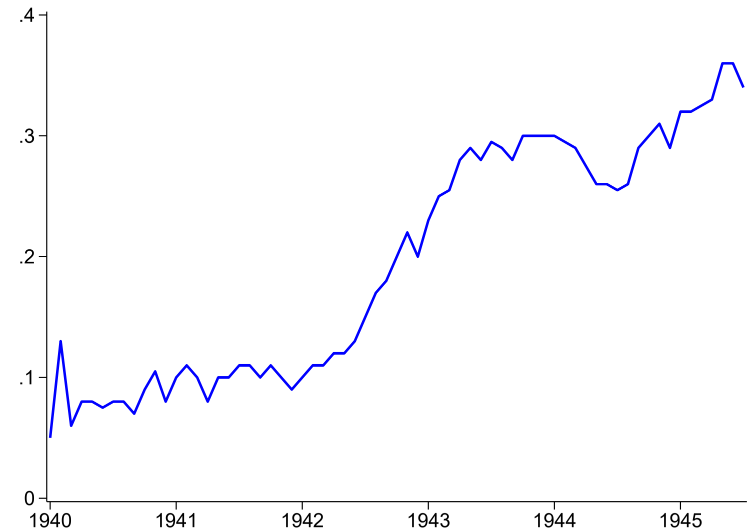
(c) Heterogeneity Based on War Manpower Commission Classification

Note: The panels show responses of TFP to 1% shocks to aircraft demand at month zero 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 (for our sample: wages were above the national median in most regions that had aircraft plats) 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, relative to those in categories 2-4. (Most aircraft plants were in labor markets classified in groups 1 and 2). The shaded areas show 90% and 95% Finlay & Magnusson (2009) weak-instrument robust confidence intervals confidence intervals. Estimates are based on local projections, with aircraft demand and its its interaction with initial capacity utilization jointly instrumented by the instrument described in Section 3 and its interaction initial capacity utilization. The specification includes month and plant-by-model fixed effects. First stage F-statistic at 12-month horizon = 27, 18, and 11 in the three panels, respectively.

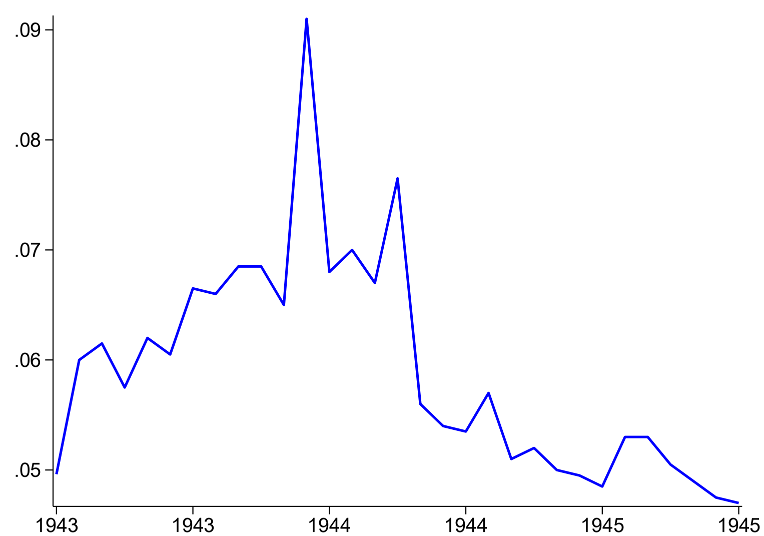
Figure A.11: Factors Affecting Productivity in Airframe Plants (Time Series)



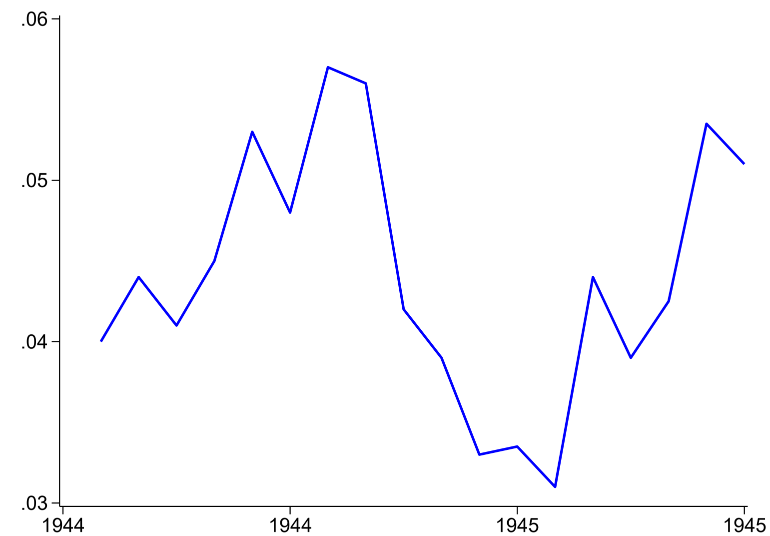
(a) Mass Production Methods



(b) Outsourcing



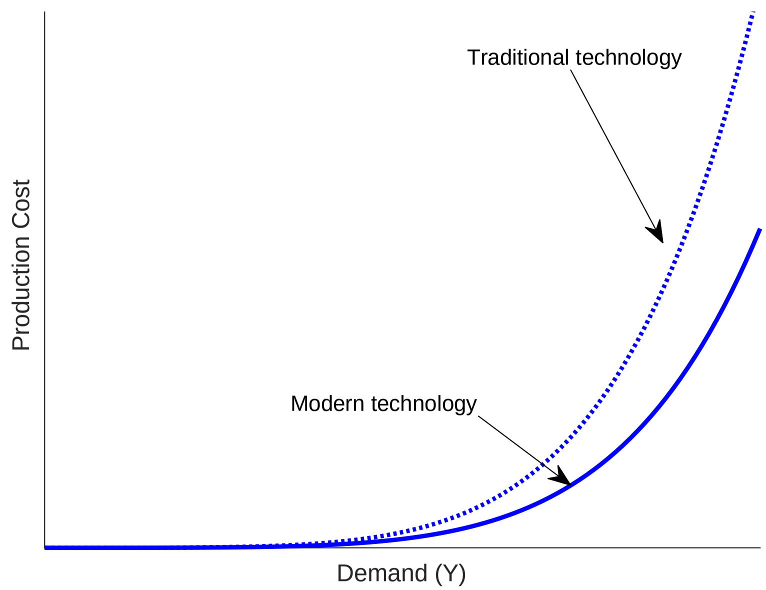
(c) Absenteeism



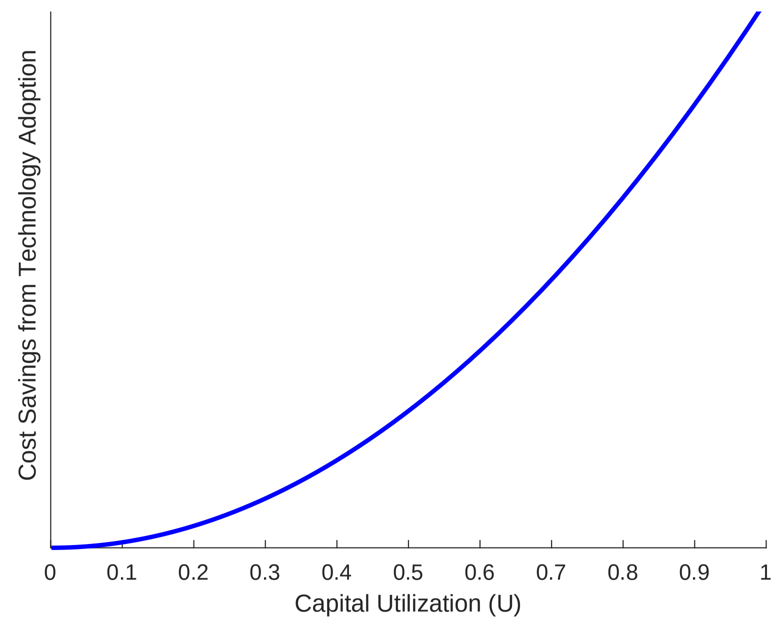
(d) Quit Rates

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). Panel (b) shows the percent of work hours in the assembly of aircraft that were outsourced to feeder plants from the median airframe plant. 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.

Figure A.12: Cost Curves in a Theory of Learning by Necessity



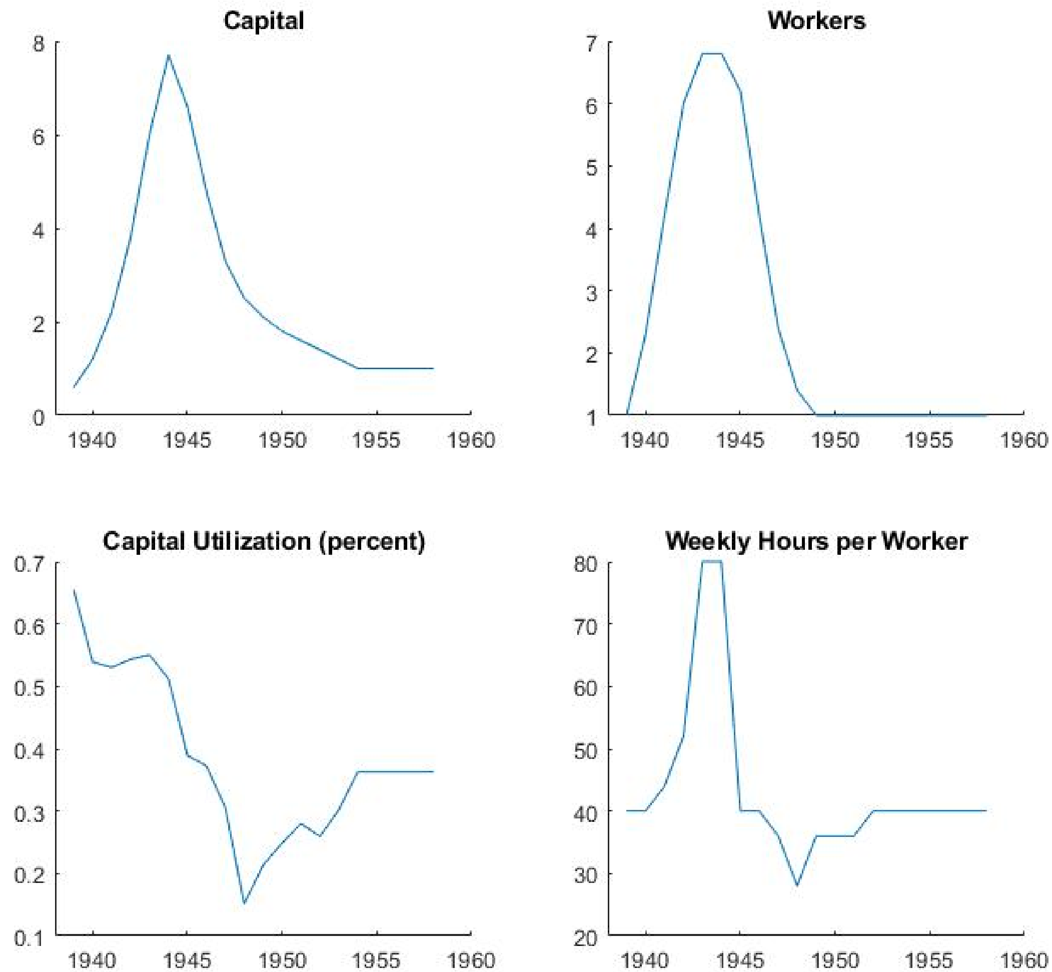
(a) Utilization Cost as a Function of Demand



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

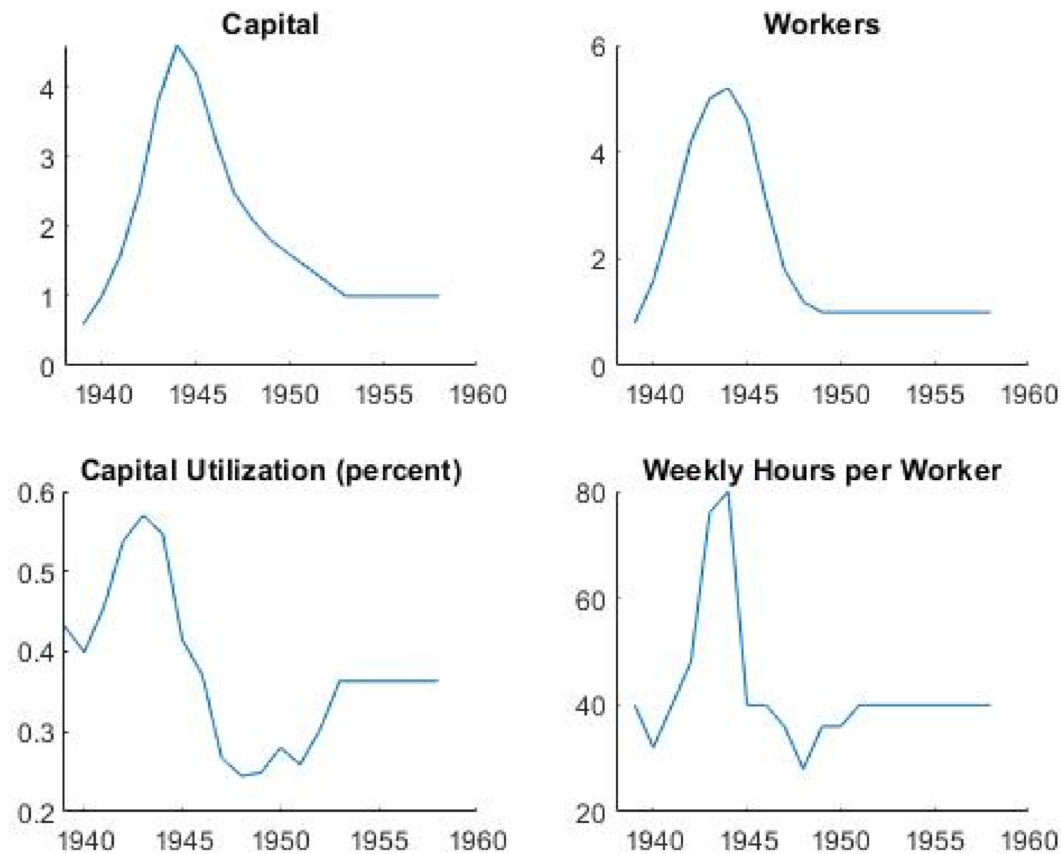
Note: The panels show cost curves arising from the theory of learning by necessity outlined in Appendix B. Panel (a) shows production (utilization) costs as a function of demand Y. The top curve represents a cost function using a traditional technology with TFP of z^T. The bottom curve represents a cost 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.13: Model Simulation: Average Plant



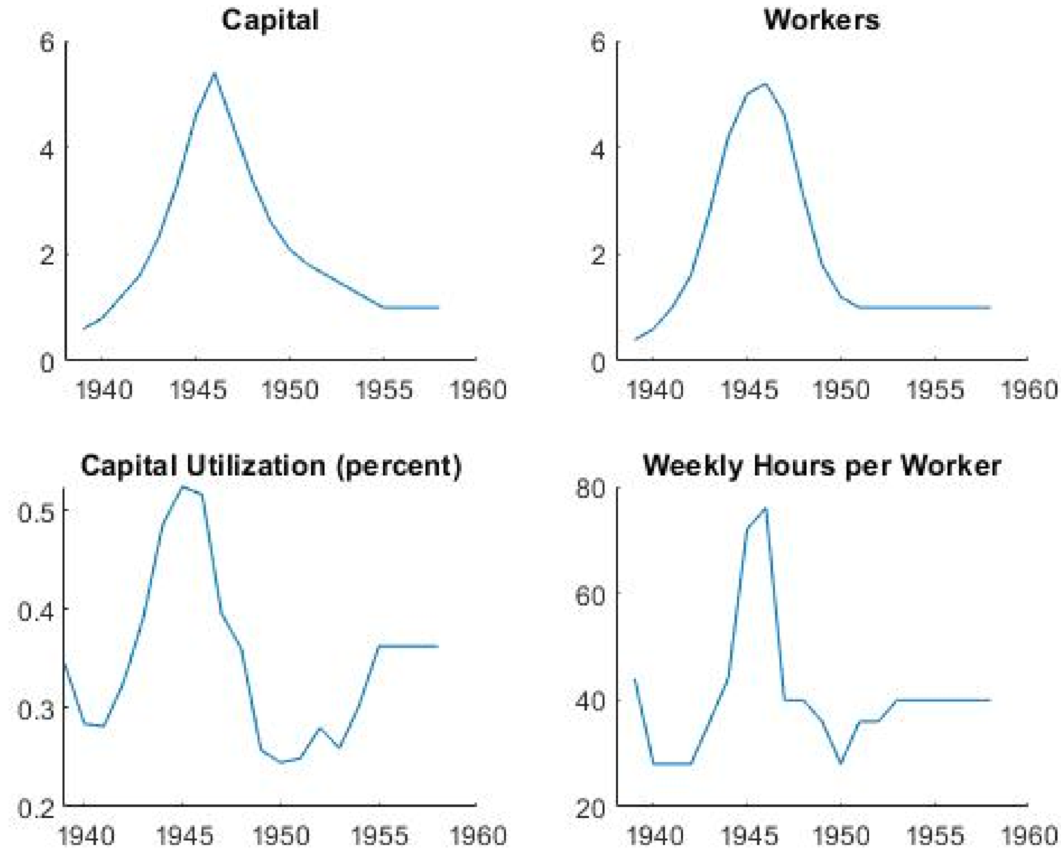
Model response of a plant to an unanticipated increase in demand announced in 1938, and matched to the production path of the average airframe plant in World War II. Full model presented in Appendix B. The top panels give the capital stock and number of workers as a multiple of the post-war steady state (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.14: Model Simulation: Low Demand Plant



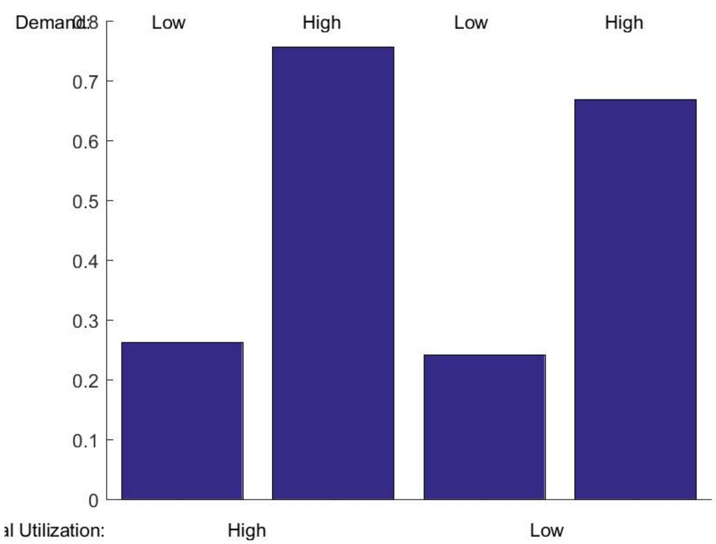
Model response of a plant to an unanticipated increase in demand announced in 1938, and matched to the production path of 25th percentile plant ("low demand"). Full model presented in Appendix B. The top panels give the capital stock and number of workers as a multiple of the post-war steady state (calibrated 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.15: Model Simulation: Low Capacity Utilization Plant

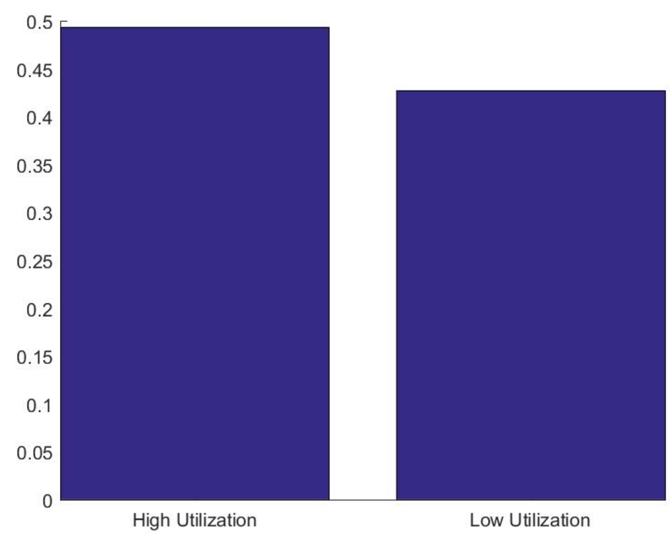


Model response of a plant to an unanticipated increase in demand announced in 1938, and matched to the production path of the average plant, but postponed by two years, reflecting a plant whose demand peaked in 1945 rather than 1943. This matches the utilization rate of the 25th percentile plant. Full 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.16: 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 25^{th} and 75^{th} 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: Correlation Between Productivity and Cumulative Output

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cumulative output	0.382***	0.406***	0.322***	0.294***	0.326***		0.278***	0.0147
	(0.0105)	(0.0111)	(0.00377)	(0.00540)	(0.00596)		(0.00967)	(0.0113)
Current output						0.268***	0.0574***	0.0426***
						(0.00670)	(0.00930)	(0.00490)
Time FE		X		X	X	X	X	X
Plant FE			X	X				
Plant*Model FE					X	X	X	X
Lagged productivity								X
Observations	2553	2553	2553	2553	2553	2491	2491	1906

Standard errors in parentheses

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

Note: The table OLS regressions of (log) aircraft produced per hour worked on (log) cumulative production, in a panel of production lines. Column (1) has no controls. The following columns include fixed effects for time (2); plant (3); time and plant (4); time and plant-by-model (5-8). Columns regress current output (6); and current and cumulative output (7) on productivity. Column (8) adds 6 monthly lags of the dependent variable (output per hour) to the regression of both output measures on productivity. Both current and cumulative output are correlated with productivity, even with the most saturated set of fixed effects. The correlation between productivity and cumulative output becomes insignificant when controlling for the lagged dependent variable.

Table A2: Robustness Checks: Labor Productivity and TFP Responses

Dependent Variable: log Aircraft per Hour Worked

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
log Aircraft Demand	0.027	0.330***	0.315***	0.222***	0.257**	0.330***	0.253***
	(0.017)	(0.098)	(0.101)	(0.073)	(0.110)	(0.098)	(0.098)
Observations	947	909	909	895	880	909	909
Adjusted R^2	0.705	0.595	0.625	0.685	0.648	0.595	0.587
First Stage F-stat		30.2	23.1	50.6	21.9	30.2	34.7

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	-0.001	0.375***	0.241***	0.311***	0.357***	0.375***	0.300***
	(0.018)	(0.080)	(0.078)	(0.064)	(0.095)	(0.080)	(0.068)
Observations	768	764	764	752	764	764	764
Adjusted R^2	0.707	0.526	0.639	0.621	0.544	0.526	0.542
First Stage F-stat		53.6	38.8	81	37.5	53.6	84.2

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. The specification is as in 2 at a 12-month horizon, $h = 12$. Column 1 shows an OLS specification. The response of productivity to aircraft demand is large in the first three months but reverts to zero in the OLS specification, as seen in Figure A.4 in the appendix. Column 2 uses (and the remaining columns use) IV, instrumenting aircraft demand with the leave-one-out instrument described in Section 3. Column 3 replaces time fixed effects with region-specific time fixed effects. 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.

Table A3: Robustness: Heterogeneity with Capacity Utilization

Dependent Variable: log Aircraft per Hour Worked

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
log Aircraft Demand	-0.024	0.213**	0.261**	0.102	0.121	0.474**	0.030	-0.003	-0.058	-2.117**
	(0.022)	(0.098)	(0.104)	(0.078)	(0.107)	(0.192)	(0.095)	(0.150)	(0.195)	(1.028)
Demand × Capacity Util.	0.078***	0.130**	0.189**	0.133**	0.133**	0.412***	0.247***	0.727**	0.678*	4.945**
	(0.025)	(0.062)	(0.082)	(0.053)	(0.058)	(0.134)	(0.054)	(0.310)	(0.355)	(2.101)
Observations	947	909	909	895	880	909	909	909	792	792
Adjusted R^2	0.708	0.623	0.575	0.700	0.679	0.451	0.603	0.640	0.624	-0.183
First Stage F-stat		15.9	9.4	26.2	11.7	5.9	18.3	15.9	20.1	3.6

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Dependent Variable: TFP

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
log Aircraft Demand	-0.076***	0.208**	0.190**	0.179**	0.179*	0.513***	0.090	-0.109	0.199	-1.237
	(0.024)	(0.083)	(0.082)	(0.072)	(0.093)	(0.172)	(0.068)	(0.140)	(0.257)	(0.761)
Demand × Capacity Util.	0.120***	0.203***	0.198**	0.160***	0.199***	0.486***	0.247***	1.148***	0.426	3.457**
	(0.028)	(0.063)	(0.078)	(0.055)	(0.061)	(0.122)	(0.051)	(0.319)	(0.504)	(1.608)
Observations	768	764	764	752	764	764	764	764	700	700
Adjusted R^2	0.714	0.567	0.588	0.645	0.594	0.293	0.587	0.583	0.495	0.089
First Stage F-stat		28	14.9	41.2	19.9	10.3	45.2	27.9	24.1	5

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 and a 1% increase in aircraft demand for plants with above median capital utilization 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. The specification is as in 3 at a 12-month horizon, $h = 12$. Column 1 shows an OLS specification. Column 2 uses (and the remaining columns use) IV, instrumenting aircraft demand with the leave-one-out instrument described in Section 3. Column 3 replaces time fixed effects with region-specific time fixed effects. Column 4 controls for (log) cumulative production, or "experience". Column 5 controls for cumulative capital investment in equipment. Column 6 controls for plant age and for the interaction between aircraft demand and a dummy equalling one if the plant is above median age. Column 7 weights observations by each plant's total production over the duration of the war. Column 8 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 9 interacts demand with a time varying measure of capital utilization (12 month lagged) instead of initial capital utilization. Column 10 instruments the time varying measure of capital utilization with capital utilization at the beginning of the war.

Table A4: 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	100	115	117	103	111	108
Firm Age (Months)	175	195	183	189	181	193	184	188
Plant Age (Months)	60	139***	123	96	106	108	88	132*
Hours per Pound	4.6	3.1	3.6	3.4	3.7	3.3	4.3	2.8
Airplanes Produced	44	81	85	60	82	59	63	75
Unit Cost (000's $)	113	111	94	130	93	129	92	126
Wing Span (Meters)	21.4	20.1	20.5	20.5	20.9	20.1	21.1	20.1
Public Plant Financing (mln $)	8.2	10.4	7.7	10.9	12.2	7.0*	9.8	9.3

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), and growth in aircraft per worker (log change from Jan 1943 to Jan 1943). 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 A5: Correlation Between Measures of Aircraft Plants' Capacity Constraints

	Capital utilization	Hours per worker	Wages	Labor market priority
Capital utilization	1			
Hours per worker	0.47***	1		
Wages	0.11	0.11	1	
Labor market priority	0.29*	0.10	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 A6: Experience, Capacity Utilization, and Post-War Patenting

	Patent Count	Citation-Weighted Patent Count
(log) Cumulative Wartime Production	-0.042	0.084
	(0.062)	(0.086)
Cum. Production × Capital U.	0.126***	0.082*
	(0.034)	(0.048)
High Capital Utilization	-0.901	2.367
	(1.289)	(1.786)
Observations	106	106
Adjusted R^2	0.480	0.479

Standard errors in parentheses

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

Note: Regression of percent growth in patents associated with a plant from 1945 to 1955 on cumulative wartime production and its interaction with a dummy equaling one if the plant had above median capital utilization at the beginning of the war. The right-hand column weights patents by their number of citations.

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.12a, 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.12a, 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.12b, 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 $K_t J\,(I_t/K_t)$ and $w_t L_t \Psi\,(D_t/L_t)$ respectively, where $J\,(.)$ and $\Psi\,(.)$ 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 $w\,(H_t)$ that are a function of annual hours. Hence $w_t = W_t + w\,(H_t)$. A linear $w\,(H_t)$ 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

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

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).

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

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

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

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

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

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 A7: 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 TPF 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 A7 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 A7, 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.13 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.[63] Higher productivity z would lower these adjustment and utilization costs and might justify the fixed cost to technology adoption A.[64]

FigureA.14 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.13 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.15 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

[63] 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.

[64] 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.16a 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.16b 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.