

Learning by Necessity

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Motivation

How do demand pressures affect the macro-economy?

Neoclassical view:

- Inflation

Keynesian view:

- Inflation
- Employment and production, if economy has “slack”

Current research agenda:

- Supply side effects on productivity
- Expansion possible even with little “slack”

Overview

Effects of large shock to G

- US WWII aircraft plants
- Detailed archival production-line data of all aircraft plants

Causal identification of demand shocks via shifting military needs

Main findings

- TFPQ \uparrow 0.3% per 1% \uparrow in demand
- **Learning by Necessity**: “Learning by doing” occurs in primarily in **capacity constrained** plants
- Running the economy “hot” could stimulate productivity.

Academic Research Context

Capacity utilization, end. growth, induced innovation

- Effects of demand → productivity implicit in endogenous growth models
- Recent advances in cycle → trend
- Literature on induced innovation, demand → *direction of technical change.* [Expand](#)

Empirical literature on fiscal multipliers

- Investigates Keynesian, wealth effect channels
- Largely ignores earlier LBD and endogenous growth literature: recent exception of Antolin Diaz and Surico (2024) [Expand](#)

Learning by doing in WWII munitions plants

- Motivating observation for endogenous growth literature
- Based on non-causal correlations
- Transmission mechanisms not well understood [Expand](#)

Historical Context and Data

Background

World War II: largest fiscal shock in US economic history

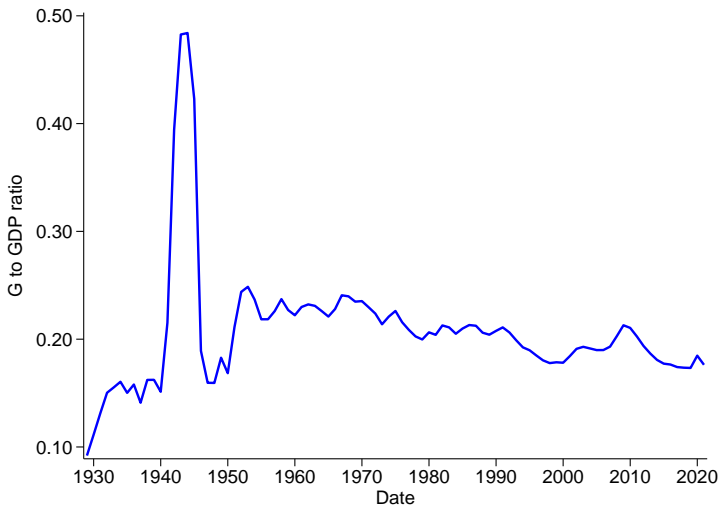
Aircraft was the largest US industry and received the most procurement \$\$

US enters the war with high unemployment, but is at full employment by December 1941

Capacity (labor and capital) hitting constraints by 1942

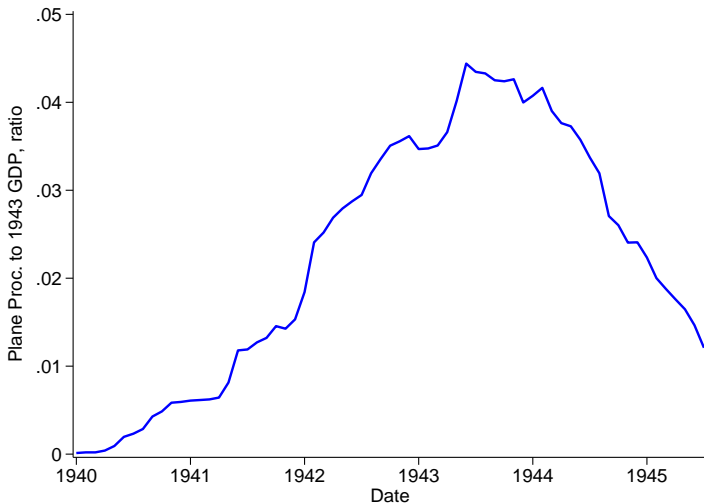
- This is the main concern of the War Production Board and War Manpower Commission throughout the war

Government Consumption: Share of GDP



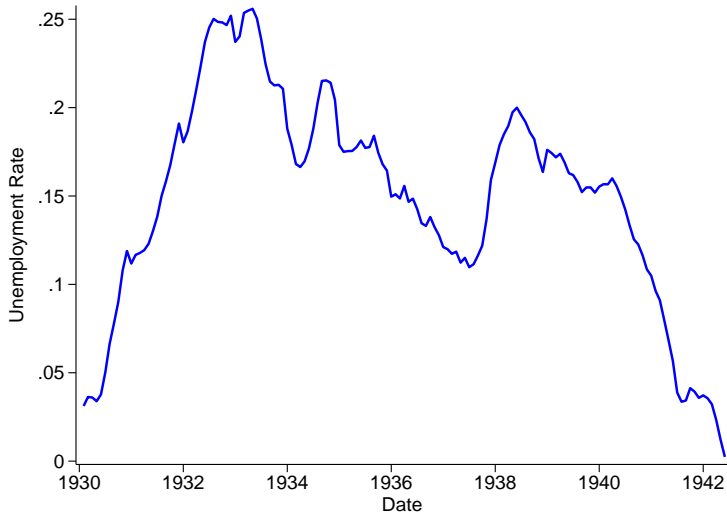
Sources: Bureau of Economic Analysis and the author

Aircraft Procurement: Share of Pre-War GDP



Source: Civilian Production Administration, Major War Supply Contracts (>\$25K), BEA, and author's calculations. Procurement is 5-month moving average and annualized.

Unemployment



Sources: NBER Macrohistory database (monthly series, line); *Historical Statistics of the United States* (annual series, Xs).

Data Sources

The US **War Production Board** kept exceptionally detailed production, input, and labor records for munitions industries

Aircraft manufacturers required to report **Aeronautical Monthly Progress Reports** (AMPR) with detail on output, inputs, and utilization

- Reported to Army Air Force (AAF) base at Wright's Field, Ohio, managing procurement and aircraft modification.
- Aircraft manufacturers were frequently audited by AAF

Additional sources: Archives of the US War Manpower Commission, Department of the Navy, Army Air Force, Convair, National War Aircraft Council

Key Raw Variables

Output per *direct* hours worked: at the *aircraft* level for last aircraft each month (plant \times model)

- Includes both onsite and outsourced production
- Similar to direct calculation of aircraft deliveries divided by payroll hours
- **Advantage:** physical output, excludes overhead, synchronizes outputs with inputs (time to build)

Capital: Total floor space used per quarter, including yard space (plant)

- Similar (but noisier) results when using capex
- **Advantage:** Most cap ex is structures, confounding land values with real investment

Hours: Total payroll of hours worked in direct production (plant \times model), and in each shift \times day (plant)

Key Calculated Variables

Capital Interpolated (linearly) from quarterly to monthly

$\frac{k}{h}$ (plant \times model): Assume plant equalizes capital/hours across production lines

Capital Utilization: $\frac{\text{Total weekly hours worked}}{168 \times \text{Max workers on first shift}}$

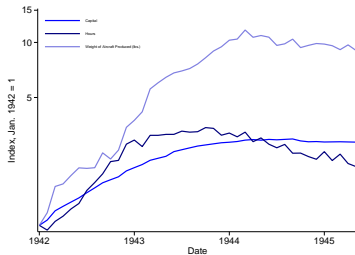
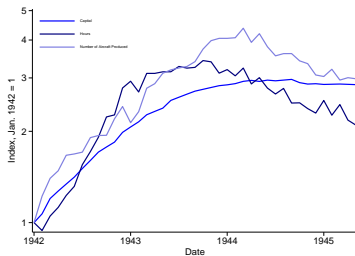
- Follows wartime measurement practice and Basu, Fernald, and Kimball (2006): shift utilization

TFP: Residualized using Cobb Douglas with labor share of $\frac{2}{3}$

Summary Statistics

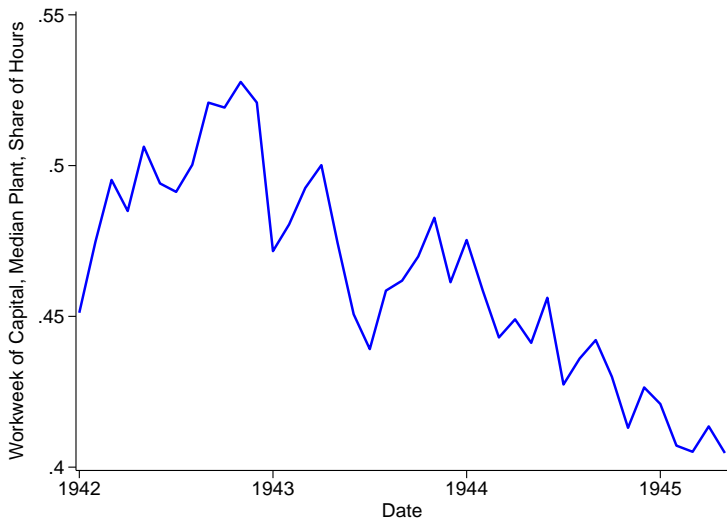
Panel A: Firm-level statistics									
	Mean	Min	P10	P25	Median	P75	P90	Max	Coef. Var.
# of plants	1.6	1	1	1	1	2	3	7	0.85
Models Produced	2.8	1	1	1	1	3	8	12	1.04
Total Sales (USD 1,000)	713,575	4,710	14,823	26,896	153,371	1,193,764	2,221,488	3,675,244	1.43
Observations:	38								
Panel B: Plant-level statistics									
	Mean	Min	P10	P25	Median	P75	P90	Max	Coef. Var.
# of models	2.0	1	1	1	1	2	4	8	0.75
Peak production employment	10,170	373	621	1,599	6,977	15,182	24,034	48,128	1.03
Avg. Monthly Production (1,000 Lbs.)	992.0	8.0	25.7	76.2	480	1,471	2,404	5,497	1.22
Cum. Investment (USD 1,000)	19,328	0	276	1,447	12,141	31,151	48,658	94,898	1.10
Peak Floor Space (1,000 sq. feet)	1,598	72	165	444	1,265	2,443	3,485	6,206	0.85
Observations:	61								
Panel C: Production-line-level statistics									
	Mean	Min	P10	P25	Median	P75	P90	Max	Coef. Var.
Peak Employment	7,465	55	481	1,465	4,556	9,818	16,021	125,360	1.63
Avg. Monthly Planes	61.0	0.50	2	11.3	36	83.8	160.6	339.1	1.10
Avg. Monthly Production (1,000s lbs.)	605.8	3.4	13.2	44.9	272.9	919.1	1,906	4,933	1.31
Observations:	141								

Aggregate Production Function



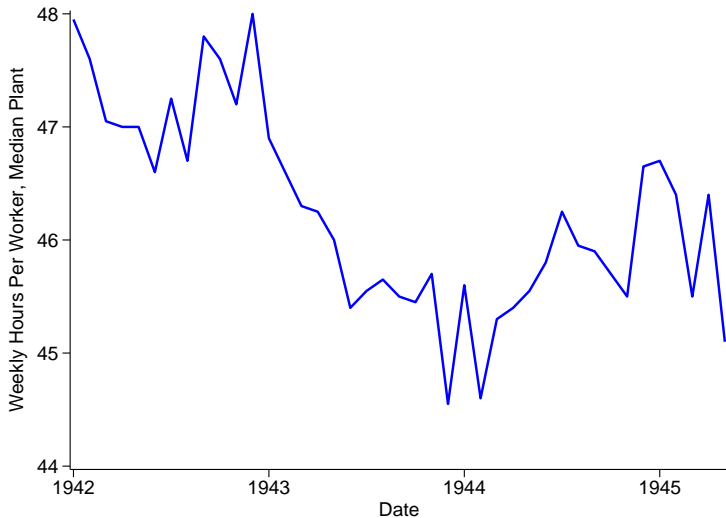
Source: AMPR and author's calculation

Capital Utilization



Source: AMPR and author's calculation

Hours per Worker



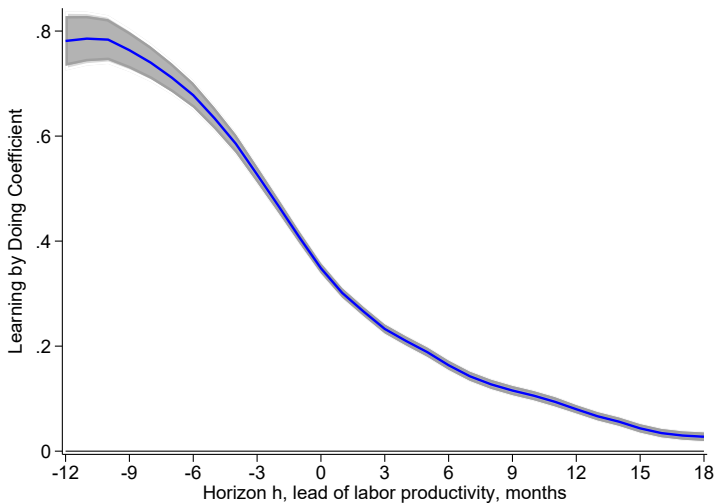
Source: AMPR and author's calculation

Shifts in Aircraft Demand and Identification

LBD: Pre-Trends

Traditional LBD regression:

$$\log(y_{mpt}) = \alpha_m + \alpha_p + \alpha_t + \beta \log(\text{CumOutput})_{mpt} + \varepsilon_{mpt}$$



Estimating Equation

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

- Local projections specification, 2 way fixed effects
- m, p, t: model, plant, month
- Dependent variable: $z_{mp,t}$, labor productivity or TFP
- Explanatory variable: $Y_{mp,t}$, aircraft demand
- Heterogeneity variable: $U_{mp,t}$, initial capacity utilization
- Include 6 monthly lags of dependent variable: aircraft demand
- **Learning by Doing**: Set $\beta^{LBN} = 0$ and estimate β^{LBD}
- **Learning by Necessity**: β^{LBD}
 - ▶ How much more “learning” in capacity constrained plants?

Instrument: Broad Aircraft Types

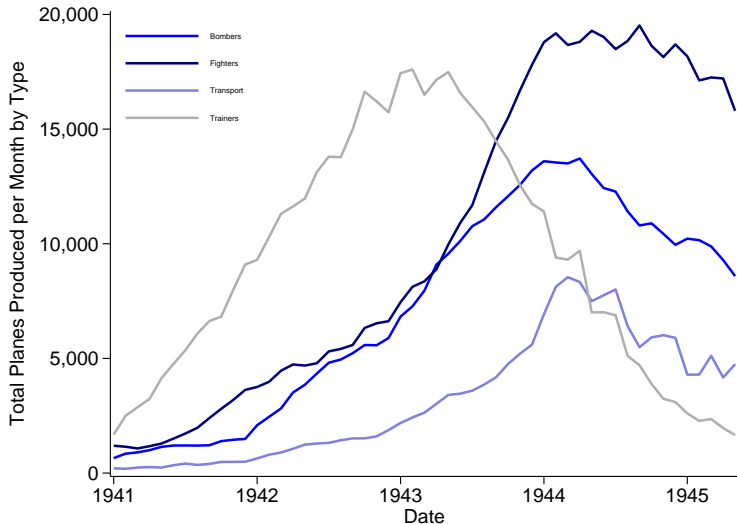
Instrument demand for aircraft from production line mp with the total production of all aircraft in broad category that includes model m , excluding mp itself (“leave one out”)

Shifting military needs for different aircraft types →
shifting demand across broad aircraft types

Identifying assumption: Shift in procurement across broad aircraft types (e.g. bomber vs. fighter) over time isn't driven by (expected) differential productivity trends.

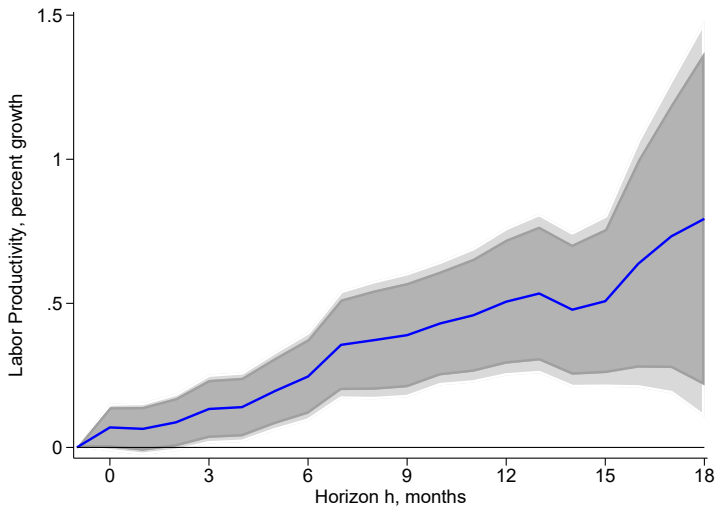
Production by Broad Aircraft Type

Monthly Number of Planes per Production Line



Results

Output per Hour Worked



Local projections response of log output per hour worked to 1% shock to aircraft demand, instrumented with the (“leave one out”) production of broad aircraft of the same broad type. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% Newey-West standard errors shaded. First stage F-stat at 12-month horizon = 24.

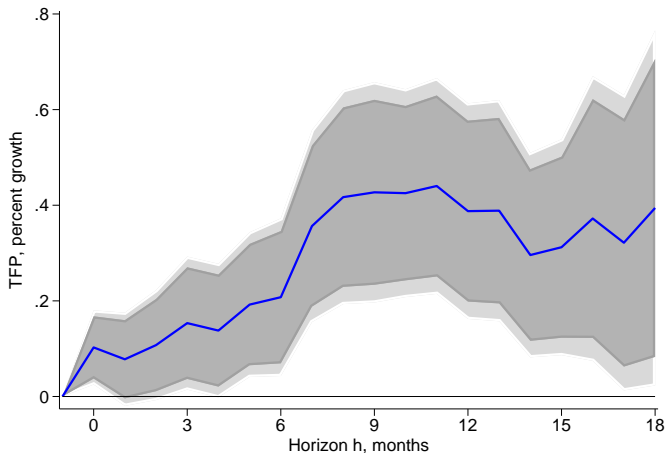
Pre-Trend

Demand Response

OLS

TFP Response

TFP Controlled for Capital Utilization



F-statistic at 12-month horizon = 32

Local projections response of log output per hour worked to 1% shock to aircraft demand, instrumented with the ("leave one out") production of broad aircraft of the same broad type. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% Newey-West standard errors shaded. First stage F-stat at 12-month horizon = 30.

Pre-Trend

OLS

No Control

Control for Learning

Investment Corr.

Goodman Bacon

Event Study

The “Learning by Necessity” Hypothesis

Productivity growth induced by demand hitting constrained capacity

Explore multiple dimensions of capacity constraints:

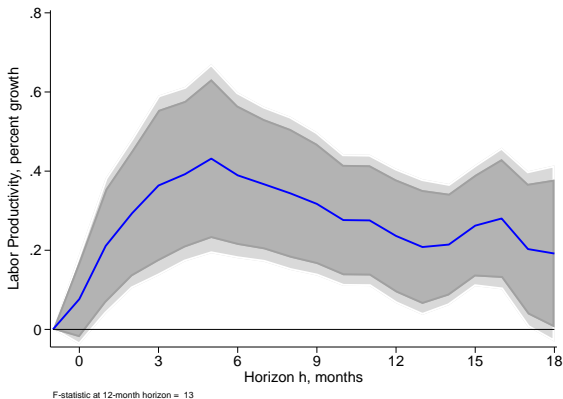
1. Capital utilization
2. Labor utilization
3. Wages

Correlations

Sum Stats

Output per Hour Worked Response to Demand

Relative Response in High Capital Utilization Plants



Local projections response of log output per hour worked to 1% shock to aircraft demand interacted with a dummy =1 if plant had above-median initial capacity utilization. These are instrumented with the (“leave one out”) production of broad aircraft of the same broad type and its interaction with the capital utilization dummy. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% standard errors shaded. F-stat at 12-month horizon = 14.

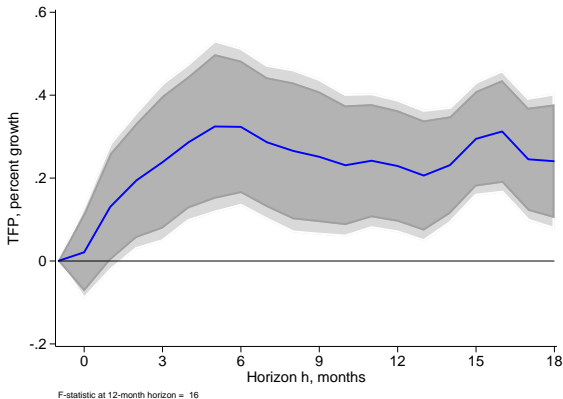
Plant Age Control

Capacity Utilization & Demand

Mod. Center Employment

TFP Response to Demand

High vs. Low Capital Utilization Plants

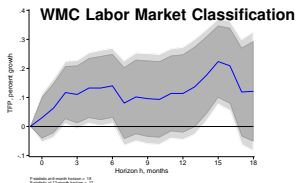
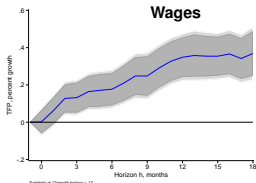
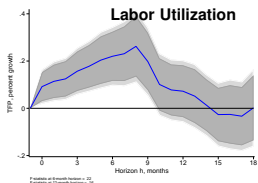


Local projections response of TFP to 1% shock to aircraft demand interacted with a dummy =1 if plant had above-median initial capacity utilization. These are instrumented with the (“leave one out”) production of broad aircraft of the same broad type and its interaction with the capital utilization dummy. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% standard errors shaded. F-stat at 12-month horizon = 15.

Plant Age Control

Relative Responses of TFP to Demand

Other Capacity Constraint Metrics



Local projections response of TFP to 1% shock to aircraft demand interacted with a dummy = 1 if plant had above-median initial hours per worker (left-hand panel) or was located in a local labor market with above-sample-median wages. These are instrumented with the (“leave one out”) production of broad aircraft of the same broad type and its interaction with the dummy. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% standard errors shaded. F-stat at 12-month horizon = 16, 17, and 12, respectively.

How Did Plants Increase Productivity?

Mechanisms

The historical narrative points to several channels through which TFP may have increased.

1. Improved production methods: Most notably move from job-shop to production line methods
2. Greater reliance on production outsourcing
3. Labor relations reduced absenteeism and turnover

History

Time Series

Move to Mass Production Methods

Bell Aircraft Corp. Volume Last Year Shows Sharp Gain

The new production unit, it is pointed out, was completed in June and was designed to enable use of "straight-line" assembly methods. In September, ground was broken for a large addition to make this plant a complete fabrication and assembly unit. As the year ended, work was being rushed to complete this plant for production use.

WSJ, Feb 6, 1942

Consolidated Vultee Aircraft Corporation

Annual Report

Mass production methods were introduced, corporation also designed and put into operation the first powered conveyor assembly line in the aircraft industry.

Annual Report 1945

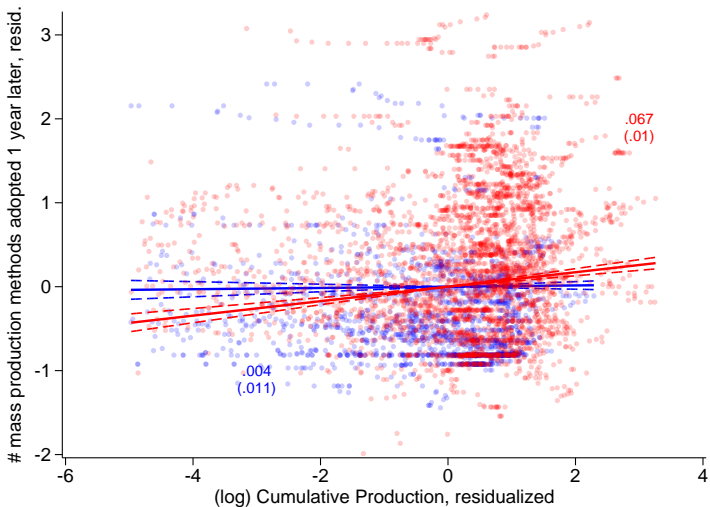
MASS PRODUCTION—The technique that used to fill this country's roads with flivvers has been successfully applied to war planes, as witness this view of an aircraft assembly line. Photo was taken at the plant of the Grumman Aircraft Engineering Corporation, Bethpage, which is busy turning out swarms of Wildcats to claw Axis and Jap bombers.

Brooklyn Daily Eagle, Oct 12, 1942

- Using newspaper articles and annual reports to create count variable for each new "mass production" technique introduced.

Sources

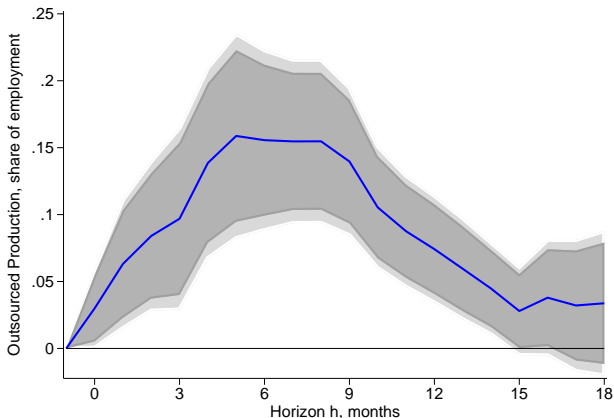
Mass Production Technique Adoption



Number of mass-production methods adopted plotted against log cumulative production 12 months earlier. Both series are residualized from time, plant, and aircraft model fixed effects. Red dots and regression lines are for plants with above median capital utilization at the beginning of the war. Blue dots and lines are for plants and below

Outsourcing

Relative Response in High vs. Low Capital Utilization Plants

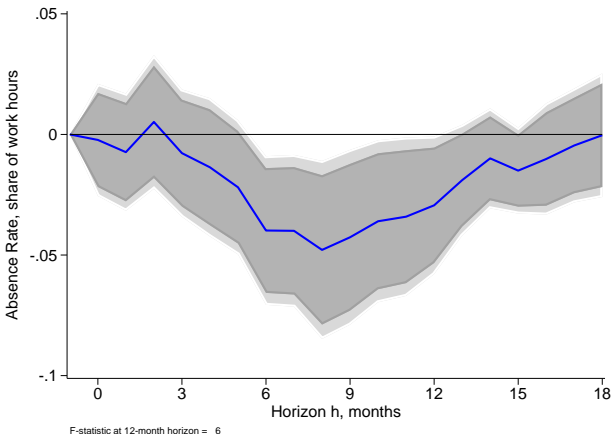


F-statistic at 12-month horizon = 13

Local projections response of percent outside production to 1% shock to aircraft demand interacted with a dummy = 1 if plant had above-median initial capacity utilization. These are instrumented with the ("leave one out") production of broad aircraft of the same broad type and its interaction with the capital utilization dummy. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% standard errors shaded. F-stat at 12-month horizon = 13

Absenteeism

Relative Response in High vs. Low Labor Utilization Plants



Local projections response of monthly hours lost due to worker absence to 1% shock to aircraft demand interacted with a dummy = 1 if plant had above-median initial capacity utilization. These are instrumented with the ("leave one out") production of broad aircraft of the same broad type and its interaction with the capital utilization dummy. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% standard errors shaded. F-stat at 12-month horizon = 6.

Learning by Necessity: Theory

One Period Version: Setup

Plant operates with technology

$$Y = z (HL)^\alpha (UK)^{1-\alpha}$$

- K, L : Capital, workers—Fixed factors
 - ▶ Face adjustment costs in dynamic model
- U, H : Capital utilization, Hours—Flexible factors
 - ▶ Convex cost to utilization: $\delta(U)K$
 - ▶ Wage convex in hours: $w(H)L$
- Have access to **T**raditional technology at zero cost or can adopt **M**odern technology at cost A . $z^M > z^T$

Cost Minimization for Given z

$$\min_{H,U} w(H)L + \delta(U)K$$

s.t.

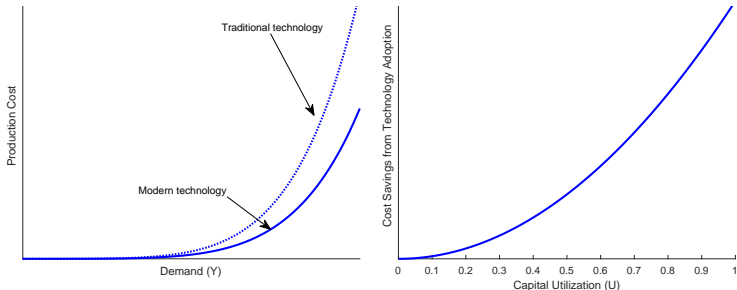
$$z(HL)^\alpha (UK)^{1-\alpha} \geq \bar{Y}$$

FOC:

$$w'(H)HL = \delta'(U)UK$$

- \Rightarrow equalizing marginal costs of utilization across factors
- Marginal utilization costs increasing in $\frac{\bar{Y}}{L^\alpha K^{1-\alpha}}$
- \Rightarrow Value of technology adoption increasing in $\frac{\bar{Y}}{L^\alpha K^{1-\alpha}}$
 - ▶ Which increases U and H in equilibrium

Cost Functions



Left hand panel: Cost as a function of demand with traditional and modern technologies

Right hand panel: Cost savings from using modern technology as a function of utilization. Adoption cost is justified at high utilization rates.

Technology Adoption and Cap. Utilization

High demand \Rightarrow high utilization \Rightarrow high marginal costs

High marginal costs \Rightarrow greater cost savings from technology adoption

Utilization endogenous, but a **sufficient statistic** for high unanticipated demand relative to current productive capacity

Full Dynamic Model in a Nutshell

Now capital and labor can adjust at convex costs

High unanticipated demand

⇒ factor accumulation over time

⇒ high utilization in the short run

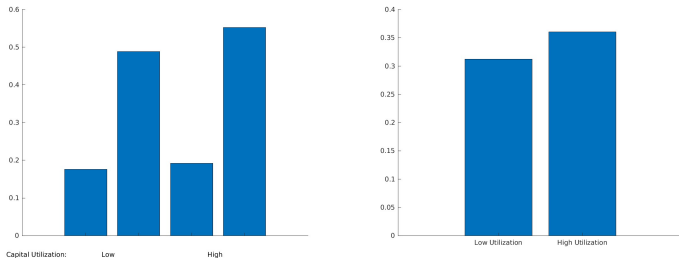
Can now simulate the theoretical equivalent of triple difference:

- High vs. low demand
- Unanticipated vs. anticipated gives high vs. low utilization
 - ▶ In data this is due to old vs. young plants

Calibrated model:

- Quantifies the (gross) cost savings due to technology adoption

Dynamic Model: Main Results



Left: Estimated cost savings of modern technology adoption (percent of average plant's NPV of costs) by demand and capacity utilization

Right: Difference between cost savings of modern technology adoption in high vs. low demand plants by capacity utilization

Better View

Wrapping Up

Contribution

Causal evidence of demand → Productivity

- Plants meet $\frac{1}{3}$ of increased demand with TFP increases.

Effect is larger in more capacity-constrained plants

- Less constrained plants respond more in terms of capacity utilization
- Necessity as the mother of innovation?

Based on newly digitized data giving comprehensive mapping of wartime aircraft production function

Simple theory of “learning by necessity”

Appendix

Academic Research Context

Learning by doing in WWII munitions plants

- Motivating observation for endogenous growth literature
- Based on non-causal correlations
- Transmission channels not well understood [Close](#)

Learning curves (based on non-causal correlations)

- Wright (1936); Middleton (1945); Searle (1945); Asher (1956); Alchian (1963); Rapping (1965); Bell & Scott-Kemmis (1990); Thompson (2001); Field (2022)
- Exception using modern data in a single plant: Levitt et al (2013)

Academic Research Context

Empirical literature on fiscal multipliers

- Investigates Keynesian, wealth effect channels
 - Largely ignores earlier LBD and induced innovation literature [Close](#)
-

Large literature reviewed in

- Ramey (2011, 2016, 2019)
- Chodorow-Reich (2019)

US wars to identify fiscal shocks

- Barro (1979); Ramey (2011); Nakamura & Steinsson (2014); Brunet (2017)

Academic Research Context

Capacity utilization, induced innovation, endogenous growth

- Effects of demand → productivity implicit in endogenous growth models
- Old literature on induced innovation hasn't been brought into discussion on fiscal policy, business cycle analysis

Close

Demand → productivity in **endogenous growth** models

- Romer (1992), Young (1991, 1998); Lucas (1993); Jones (1995); Arthur (1989), Benigno & Fornaro (2018); Anzoategui et al (2019)

Demand scale effects

- Hall (1989); Basu and Fernald (1997); Davis & Weinstein (2003); Acemoglu & Lim (2004); Costinot et al (2019)

Induced innovation hypothesis

- Hickman (1957); Fellner (1961); Kennedy (1964); Samuelson (1965); Drandakis & Phelps (1966); Phelps

Historical Support for Identification

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.

Manpower Problems in the Airframe Industry

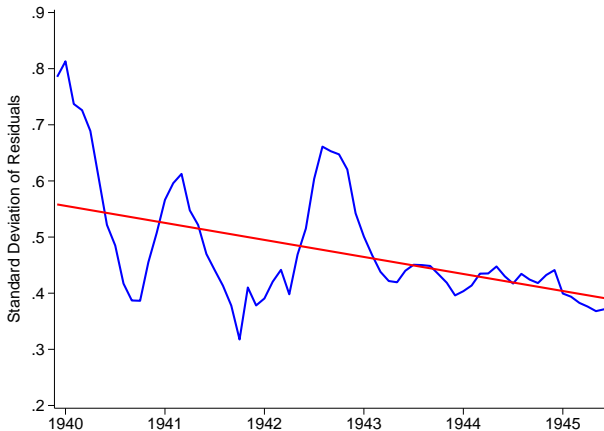
Report, War Manpower Commission, Sep 1943, National Archives

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.

WPB Production in 1944

Report, War Production Board, 1944

Standard Deviation of Productivity Across Production Lines



Standard deviation of log aircraft per hour worked across airframe manufacturers in each month, 5-month moving average. Residualized from time and aircraft model fixed effects. Results are similar when excluding time fixed effects. Source: AMPR and the author. [Return](#)

Sample Page from AMPR Form

CONSOLIDATED AIRCRAFT CORPORATION
SAN DIEGO, CALIFORNIA

CONFIDENTIAL Subject Form No. AF-507-02
Revised August 12, 1943

AERONAUTICAL MONTHLY PROGRESS REPORT
No. 4 LABOR AND FACILITY UTILIZATION
For the Week April 10, 1943
(For the Week Ending Nearest the 15th of the Month)

Aircrafts
Gleizers
Targets
Engines
Propellers

CONSOLIDATED VULVE AIRCRAFT CORPORATION
Facility San Diego 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

Number of Workers (or per 100)	1st Shift (Day)			2nd Shift (Evening)			3rd Shift (Night)		
	Mon	Tue	Wed	Mon	Tue	Wed	Mon	Tue	Wed
18,871	6	8	8	9,216	6	8	235	6	6-5
30	6	6	6	234	6	6			
1,556	7	8	8	1,597	7	8			
Total				18,846			235		

Remarks: None

B. Direct Workers And Man-Hours Actually Worked

- Total number of direct workers actually worked on factory job 24,246
- Man-hours actually worked by direct workers during week 1,134,751
- Average hours actually worked per direct worker (B ÷ A) 46.82

C. Shift And Week-End Direct Employment

	1st Shift (Day)	2nd Shift (Evening)	3rd Shift (Night)
1. Man-hours through factory progress number of work for any one shift	49,052	12,704	10,099
2. Saturday (Total number of work)	22,147	12,147	9,471
3. Sunday (Total number of work)	1,035	1,032	885

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

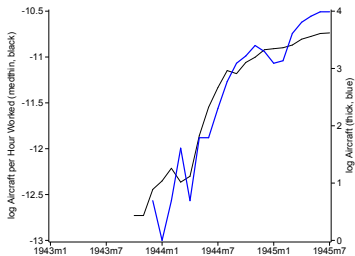
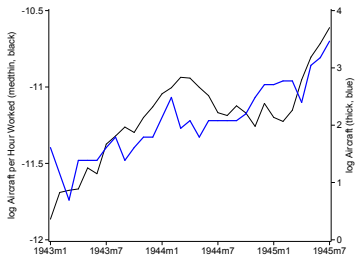
1. Sick 24,375 2. Personal 37,567 3. Other 62,112

CONFIDENTIAL

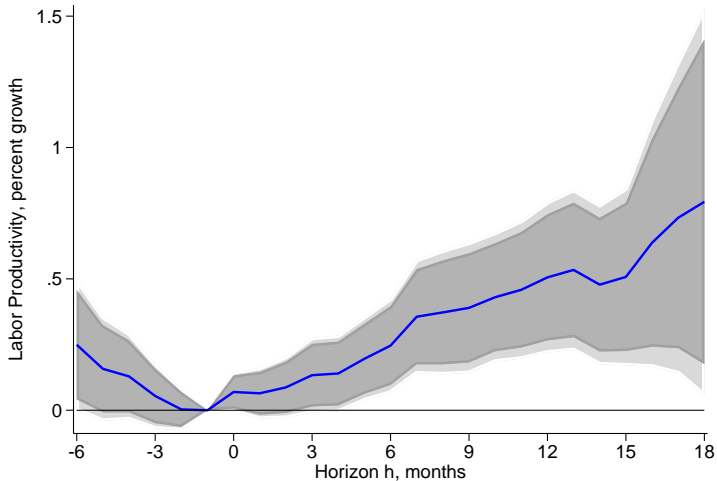
C-54 Production in Two Douglas Aircraft Plants

Santa Monica (top); Chicago (bottom)

Shifting production to
new plant within firm
→ productivity decline
→ lower output



Pre-Trend in Output Per Worker

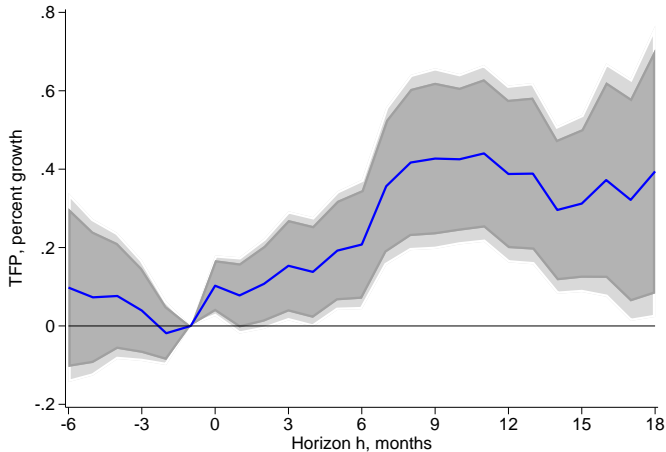


F-statistic at 12-month horizon = 25

Local projections response of log output per hour worked to 1% shock to aircraft demand, instrumented with the (“leave one out”) production of broad aircraft of the same broad type. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output, and control for (log) of total workers. 90% and 95% Newey-West standard errors shaded. First stage F-stat at 12-month horizon = 24.

[Return](#)

Pre-Trend in TFP



F-statistic at 12-month horizon = 32

Local projections of output per worker response to 1% increase in demand. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of dependent variable and output.

[Return](#)

Historical Support for Identification (ii)

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.

WPB Production in 1944
Report, War Production Board, 1944

Return

Historical Support for Identification (iii)

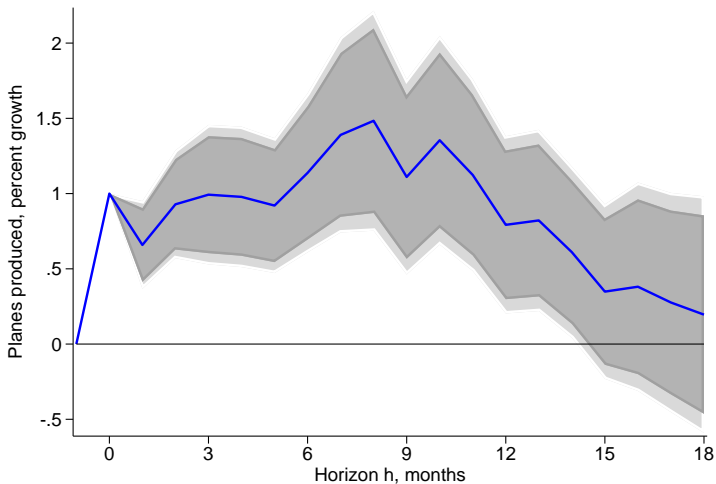
[In the early war years, Air Corps Tactical School (ACTS) instructors] believed that bombers had enough self-contained firepower to defend themselves on the way to their targets.

Clearly after the second Schweinfurt raid [of 17 August 1943, where bomber squads saw massive losses] it was time for a change in the doctrine of unescorted strategic bombing. The bomber forces could not continue to sustain such heavy losses.

A directive on fighter allocation was released on October 31 that stated, “the primary role of all U.S. fighter units in the U.K. until further notice will be the support and protection of the heavy bombers”

*The Evolution of the Long-Range Escort Doctrine in World War II
Leshner (1988)*

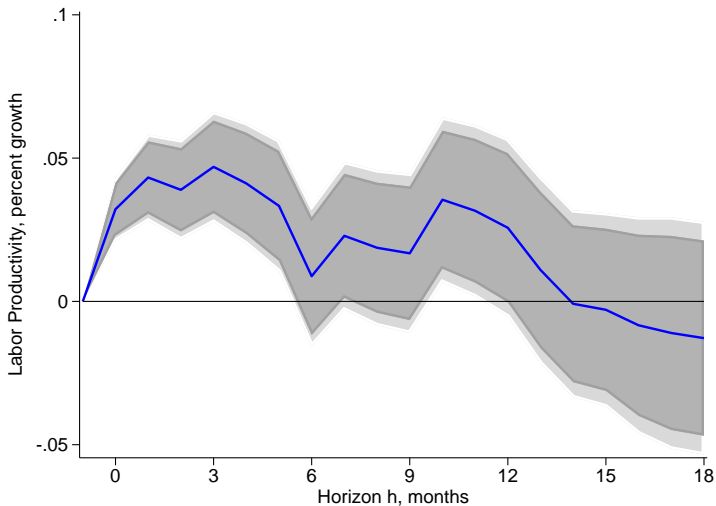
Output's Own Response to Demand



F-statistic at 12-month horizon = 25

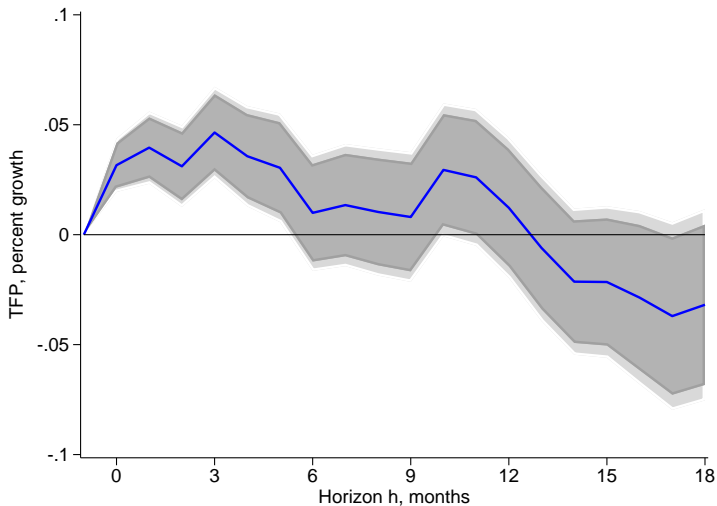
Local projections response of log output to 1% shock to aircraft demand, instrumented with the ("leave one out") production of broad aircraft of the same broad type. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% Newey-West standard errors shaded. First stage F-stat at 12-month horizon 13 / 45

Output per Worker Response: OLS



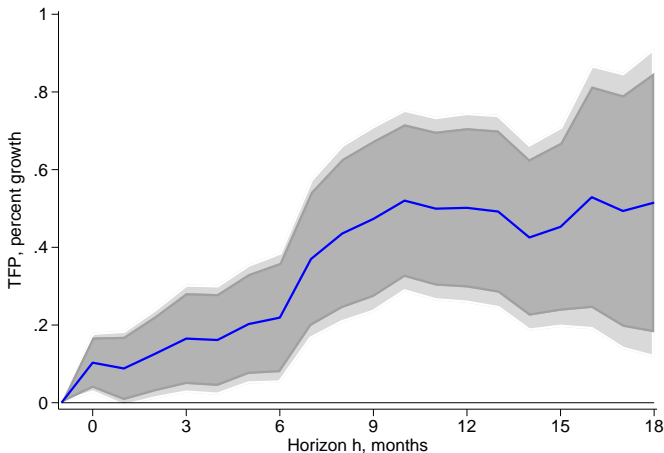
Local projections response of log output to 1% shock to aircraft demand, OLS. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% Newey-West standard errors shaded.

TFP Response: OLS



Local projections response of TFP to 1% shock to aircraft demand, OLS. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% Newey-West standard errors shaded.

TFP Response: No Capital Utilization Control

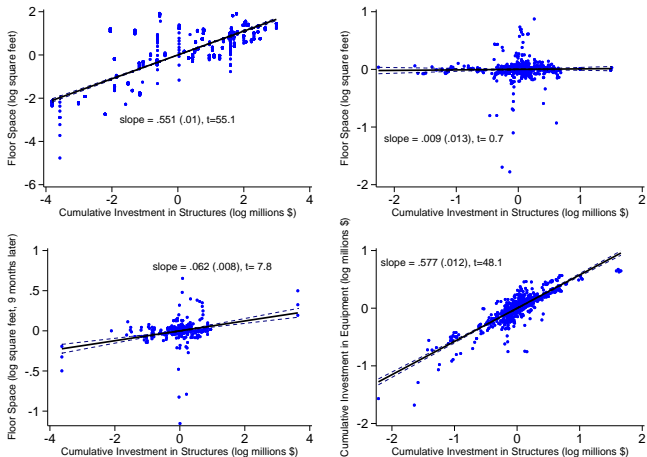


F-statistic at 12-month horizon = 33

Local projections response of TFP, not adjusted for capital utilization, to 1% shock to aircraft demand, instrumented with the (“leave one out”) production of broad aircraft of the same broad type. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of production. 90% and 95% Newey-West standard errors shaded.

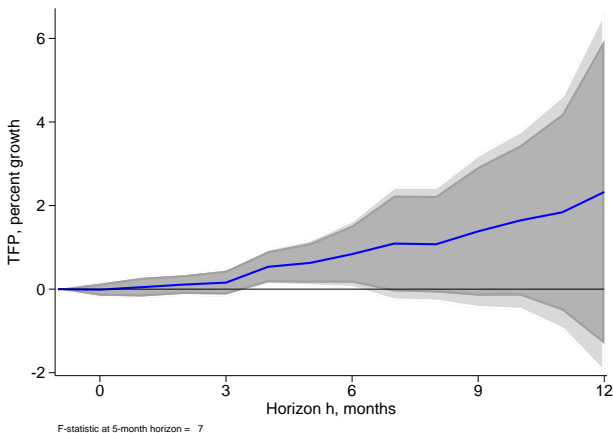
First stage F-stat at 12-month horizon = 32. [Return](#)

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

TFP Response: Addressing Heterogeneous Treatment Effects Bias



Local projections response of TFP, adjusted for capital utilization, to 1% shock to aircraft demand, instrumented with the (“leave one out”) production of broad aircraft of the same broad type interacted with a dummy variable equalling one for the first half of the sample, as suggested by Goodman Bacon (2021). Includes month and plant \times model (production line) fixed effects, 6 monthly lags of production. 90% and 95% Newey-West standard errors shaded.

First stage F-stat at 12-month horizon = 7.5. [Return](#)

Capacity Utilization and Demand

Despite enormous concerns about labor and facilities shortages, the historical record suggests this didn't affect demand patterns.

[t]he Advisory Commission to the Council of National Defense announced that the criteria for placing orders under negotiated contracts should be, as far as possible, "the use of plants which now have excess or unused capacity and the selection of localities where there are reservoirs of unused labor... Despite this announcement most defense orders continued to be placed with customary suppliers."

Army and Industrial Manpower
Fairchild and Grossman, 1958

Correlates with Modification Center Employment

Dependent variable	(1) Hours in plant	(2) Productivity	(3) Productivity	(4) Productivity	(5) Productivity
Mod. Ctr. Employment	0.912*** (.040)		-0.018 (.051)	0.033 (.121)	-0.021 (.086)
Hours in Plant		-0.002 (0.008)		-0.047 (0.101)	
Mod. Ctr. × High Initial Cap U.					0.005 (0.104)
<i>N</i>	179	2,550	153	153	153
adj. R^2	0.830	0.138	-0.035	-0.042	-0.044

Standard errors in parentheses

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

Return

Capacity Constraint Indicators

Correlations at beginning of war production drive

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

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

Return

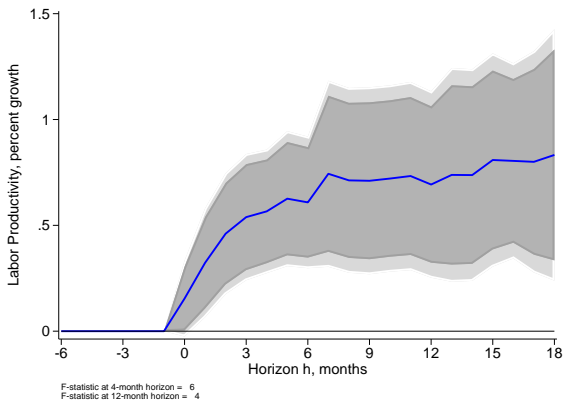
Who Were the Constrained Plants?

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

Return

Output per Worker Response to Demand - Controlling for Plant Age

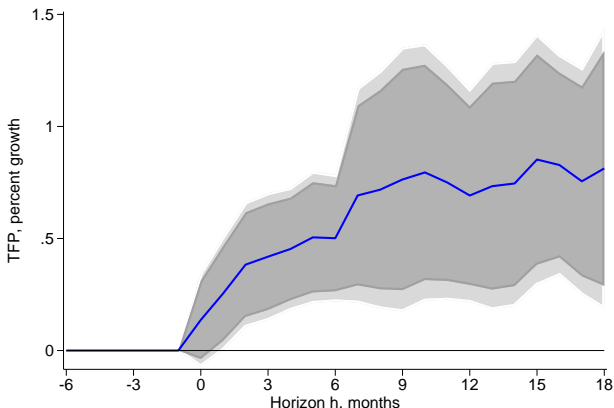
Relative Response in High Capital Utilization Plants



Local projections response of log output per hour worked to 1% shock to aircraft demand interacted with a dummy =1 if plant had above-median initial capacity utilization. These are instrumented with the (“leave one out”) production of broad aircraft of the same broad type and its interaction with the capital utilization dummy. Controlling for plant age and the interaction between aircraft demand and a dummy =1 if plant is above median in age. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 90% and 95% standard errors shaded.

TFP Response to Demand - Controlling for Plant Age

Relative Response in High Capital Utilization Plants



F-statistic at 4-month horizon = 7
F-statistic at 12-month horizon = 3

Local projections response of TFP to 1% shock to aircraft demand interacted with a dummy =1 if plant had above-median initial capacity utilization. These are instrumented with the ("leave one out") production of broad aircraft of the same broad type and its interaction with the capital utilization dummy. Controlling for plant age and the interaction between aircraft demand and a dummy =1 if plant is above median in age. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output. 95% standard errors shaded. F-stat at

12-month horizon = 3. [Return](#)

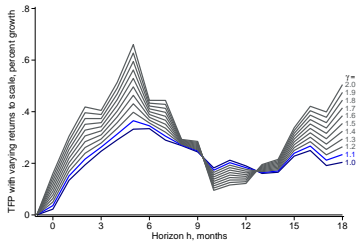
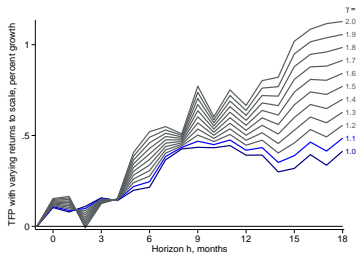
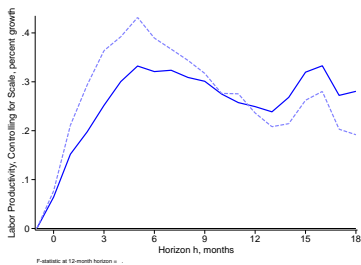
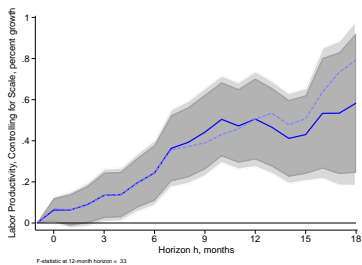
Production Methods

Before 1940 airplanes were largely manufactured by hand-work; by the end of 1942 the transition to mass production methods had occurred.

Nobody had ever sold enough airplanes to finance mass production tooling, or to justify its cost. For markets that bought one or two airplanes at a time, or a few dozen at the most, it was plain horse sense to custom-build them... Mass production required machines of complexity and precision far beyond anything ever before attempted, and there was no incentive to try it until airplanes were ordered by thousands.

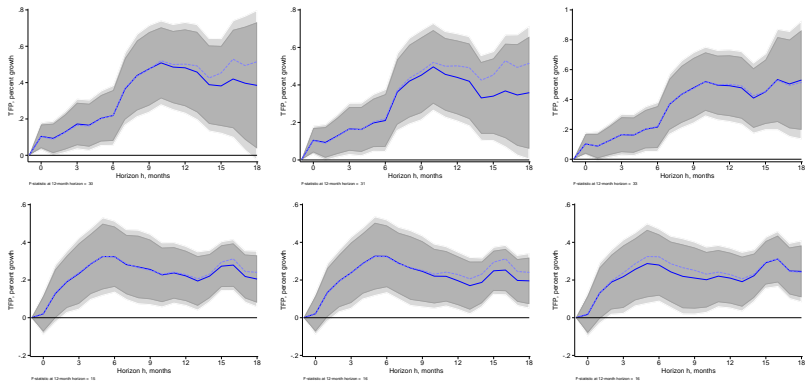
In peacetime, the aircraft industry had had no opportunity to acquire familiarity with line production techniques; these techniques were not needed to meet peacetime production demands and were not used because of their high cost at peacetime volumes of output.

TFP or Economies of Scale?



L-R: Labor Productivity Response; Labor Productivity Response: High vs. Low Capital Util.
T-B: Controlling for Growth of Factors of Production; Residualizing with a Range of Scale Parameters

Controlling for Spillovers from Peer Production Lines



L-R: TFP Response; Relative TFP Response: High vs. Low Capital Utilization Plants

T-B: Control: Average Productivity Growth of All Other Production Lines Producing Same Broad Type; Control: Average Productivity Growth of All Other Production Lines Using the Same Motor Manufacturer; Control: Average Productivity Growth of All Other Production Lines Using the Same Motor Manufacturer

Return

Outsourcing

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, including two groups that until then had been little used by heavy industry, women and [African Americans], but it put a heavier burden on management and proved more difficult to schedule accurately than had previous methods.

Craven and Gate vol. 6, 1955

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.

Taylor and Wright, 1947

Labor Relations

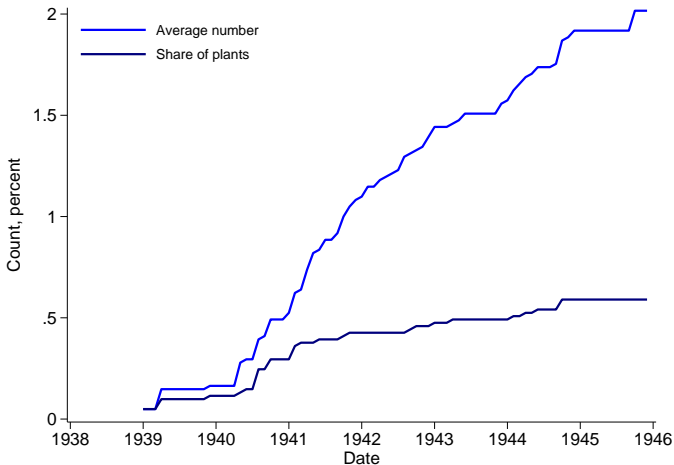
The turnover in 1943 amounted to more than eighty percent of the work force...

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...

Many and ingenious were the devices used to cope with the problem. Factories sent telegrams to the homes of absentees, inquiring after their welfare and telling them how they were needed in the war. Others sent visiting nurses to make first hand check-ups... Surveys searched for the causes of absenteeism... Working conditions were improved...

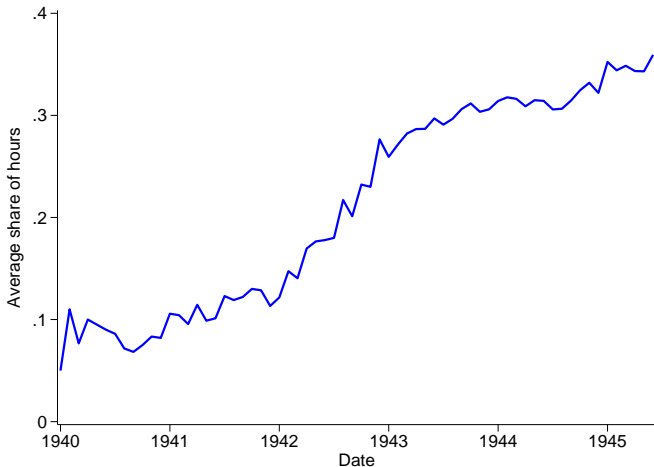
"Exit interviewers" attempted to learn the reason for every voluntary quit; management sought to eliminate every possible focus of discontent.

Mass Production: Time Series



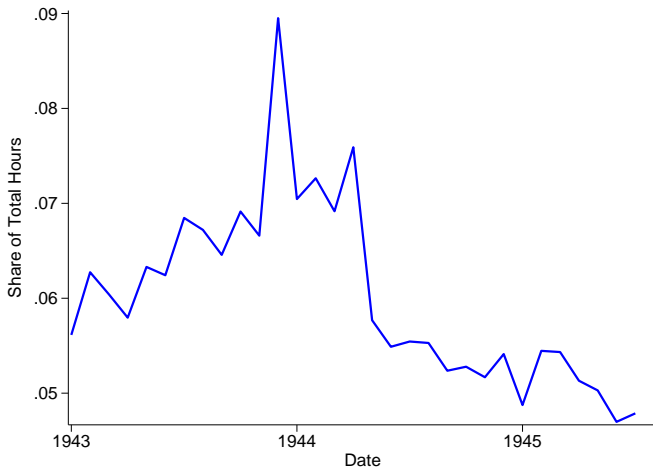
Cumulative share of plants adopting mass production methods (lower line) and the number of methods adopted by the average plant (top line). [Return](#)

Outsourcing: Time Series



Share of work hours in the assembly of aircraft that were outsourced to feeder plants from the median airframe plant. [Return](#)

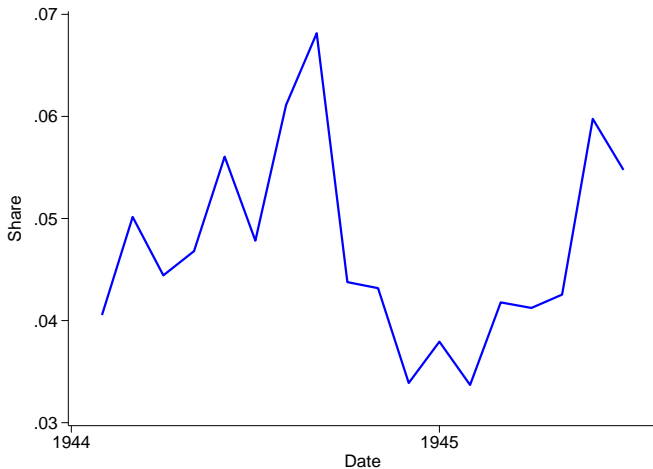
Worker Absence: Time Series



Share of worker-hours lost due to worker absence in the median plant.

[Return](#)

Quit Rates: Time Series



Share of workers quitting per month in the median plant.

[Return](#)

News Sources for Mass Production Methods

Sources

- Business Week
- Fortune Magazine
- New York Times
- Wall Street Journal
- Local newspapers at locations of all plants (newspapers.com)
- Annual reports taken from Mergent archives and Proquest

Search terms Company names plus:

- “mass” “production” within 5 words of each other
- “assembly” “line” within 5 words
- “automotive”
- All articles human read

Learning by Necessity: Dynamic Theory

Setup

Plant operates using a Cobb-Douglas production function:

$$Y_t \leq z (H_t L_t)^\alpha (U_t K_t)^{1-\alpha},$$

Capital and workers accumulate according to

$$K_{t+1} \leq I_t + (1 - d) K_t;$$

$$L_{t+1} \leq L_t + D_t;$$

Plant faces convex costs to:
Investment

$$K_t J(I_t/K_t)$$

Capital utilization

$$\delta(U_t)$$

Hiring/firing

$$w_t L_t \Psi(D_t/L_t)$$

Labor utilization

$$W_t + w(H_t)$$

Cost Minimization

$$\min_{D_t, L_{t+1}, I_t, K_{t+1}, H_t, U_t} \sum_{t=0}^{\infty} \prod_{j=0}^{t-1} \left(\frac{1}{1+r_j} \right) \text{Cost}_t$$

Where:

$$\text{Cost}_t = W_t L_t + L_t w(H_t) + L_t [W_t + w(H_t)] \Psi(D_t/L_t) + K_t \delta(U_t) + K_t J(I_t/K_t) + r_t K_t$$

S.t. capital and worker accumulation and satisfying demand Y_t

Return

Functional Forms

Investment costs:

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

Utilization costs

$$\delta(U) = \delta_0 \frac{U}{1-U}$$

Hiring/firing:

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

Labor utilization / overtime pay:

$$w(H) = \bar{w} [H + \omega (H - FT) \Xi (H > FT)],$$

where ω is the overtime rate, FT is full time hours, and Ξ is an indicator function equal to one if hours exceed full time and zero otherwise.

Calibration

Calibrating steady state to post-war period (matched exactly):

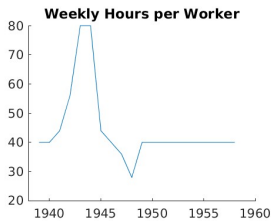
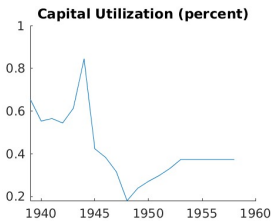
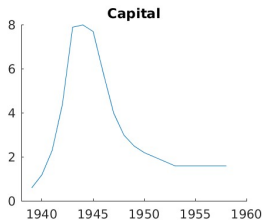
Parameter/Target	Value	Source
d	0.08	Literature
r	0.03	Post war data
$\bar{H} = FT$	0.24	40 hour workweek
ω	0.5	Typical overtime rates
$\frac{W}{\bar{w}FT}$	0.25	Typical overhead
U	0.36	$1\frac{1}{2}$ daily shifts, 5 days a week
α	$\frac{2}{3}$	Post-war labor share

Calibrating to post-war capital and labor overhang:

Parameter	Value	Target 1944 - 48	Value
ϕ	1.2	Capital reduction	1.12 log points
ψ	0.975	Worker reduction	1.65 log points

Simulation: Average Firm

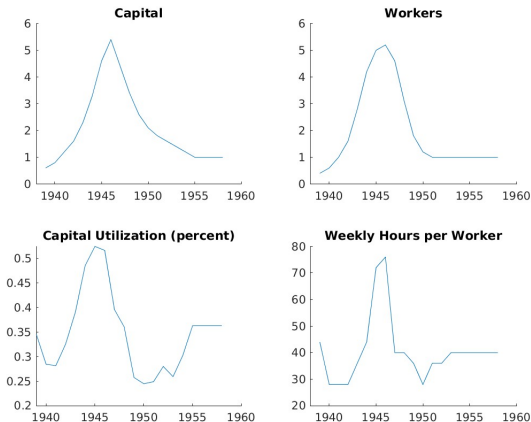
Hit plant with unanticipated (“MIT”) World War II shock to demand starting in 1938 [Return](#)



Simulation: Low Demand

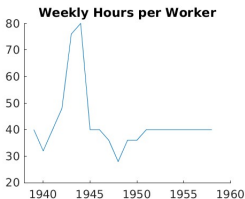
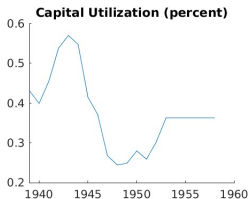
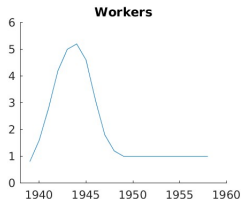
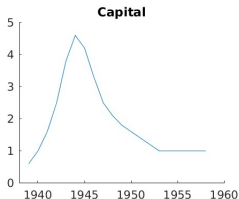
Scale shock to plant at 25 percentile of demand [Return](#)

Lowers factor accumulation, utilization, and costs → lower incentive to adopt technology



Simulation: Low Capacity Utilization

Giving plant 2-year advance warning allows it to accumulate factors to match plant at 25 percentile of utilization [Return](#)



“Experiment”

Average firm saw 33% productivity increase

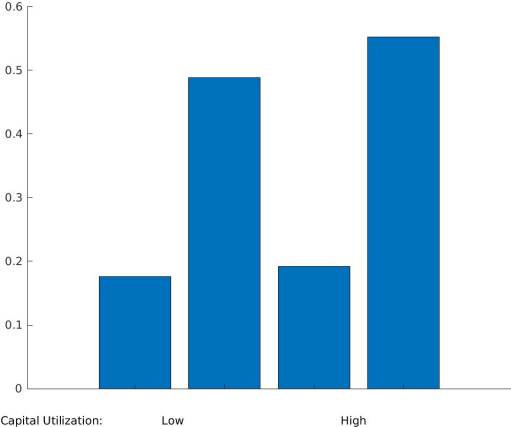
Simulate cost reduction from technology adoption that increases z from 75% of post-war TFP to post-war TFP

Compare high to low demand, matching cumulative orders from 75th and 25th percentile of plants operating during war

Compare high to low utilization giving (no) advance warning of war to match 75th and 25th percentile of plants

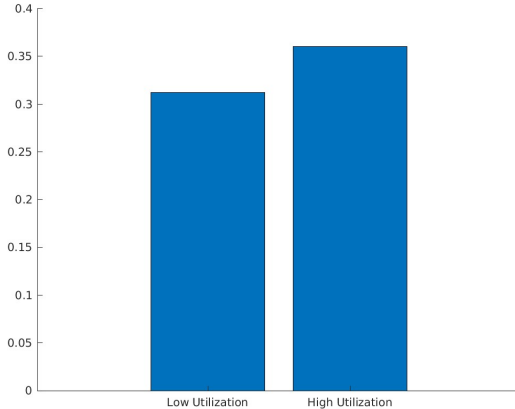
[Return](#)

Cost Savings from Technology Adoption



Return

Relative Cost Savings from Tech Adoption



Return