

Learning by Necessity:
Government Demand, Capacity Utilization, & Productivity

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Overview

Study effects of G on productivity in US WWII plants

Detailed archival production-line data of all aircraft plants

Shifting military needs → **causal identification of demand shocks**

TFPQ \uparrow 0.2% per 1% \uparrow in demand

“Learning by Necessity” (Evidence + Theory)

- Plants with “slack” increase capacity utilization in response to demand.
- “Learning by doing” occurs in primarily in capacity constrained plants
- Suggesting that running the economy “hot” could stimulate productivity (“reverse hysteresis”).

Academic Research Context

Capacity utilization, endogenous 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 [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

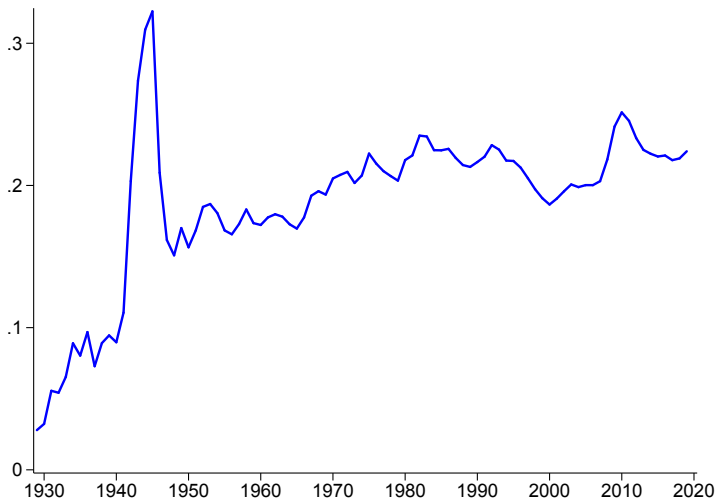
Aircraft was the largest US industry and received the most procurement \$s

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

Capacity (labor and capital) hitting constraints by 1942

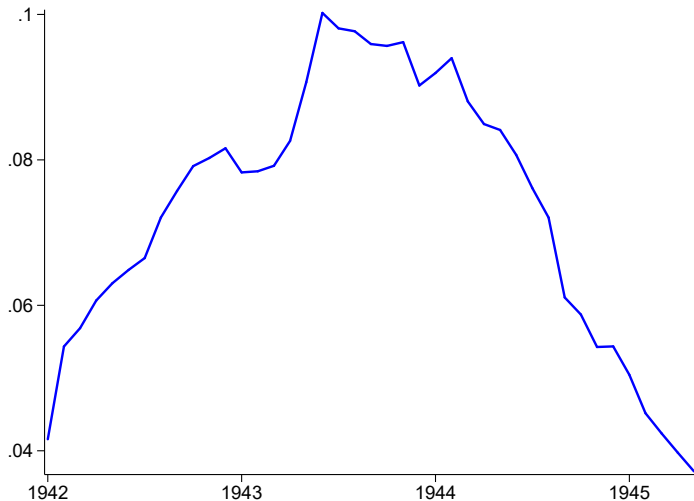
- This is the main concern of the War Production Board and War Manpower Commission throughout the war

Government Consumption: Share of GDP



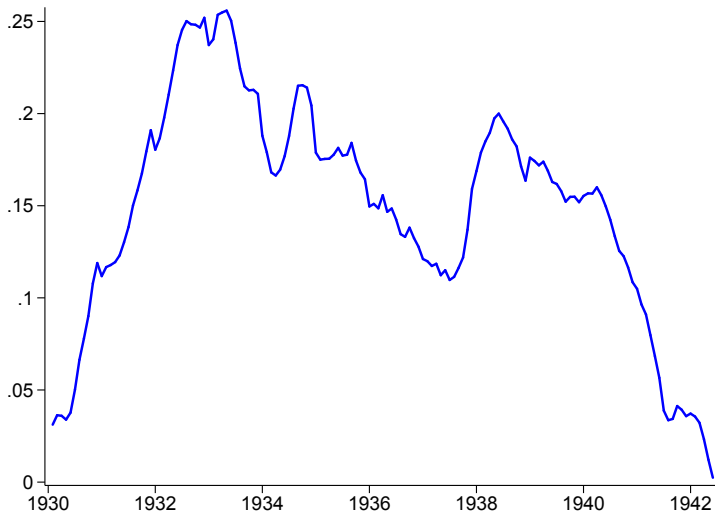
Sources: Bureau of Economic Analysis and the author

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



Source: NBER Macrohistory database

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; Google patents

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

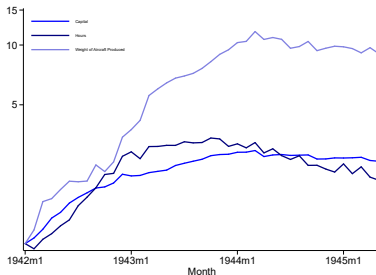
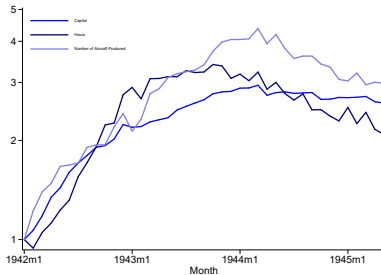
$\frac{k}{h}$ (plant \times model): Assume plant equalizes capital/hours across production lines

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

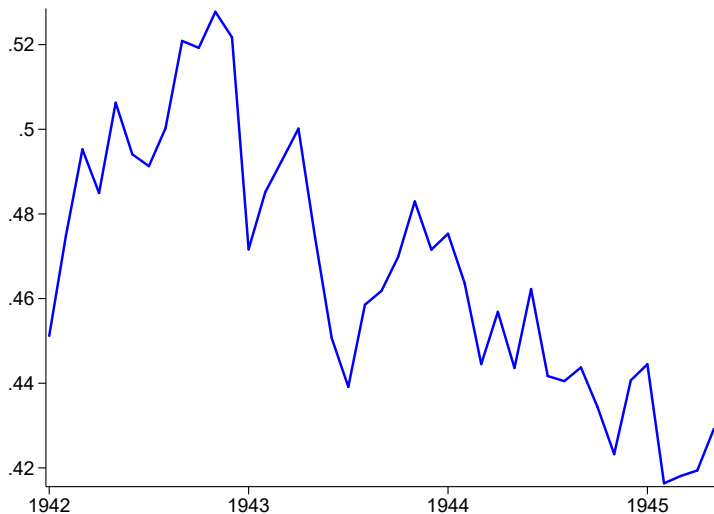
- Follows wartime measurement practice and Basu, Fernald, and Kimball (2006): shift utilization

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

Aggregate Production Function

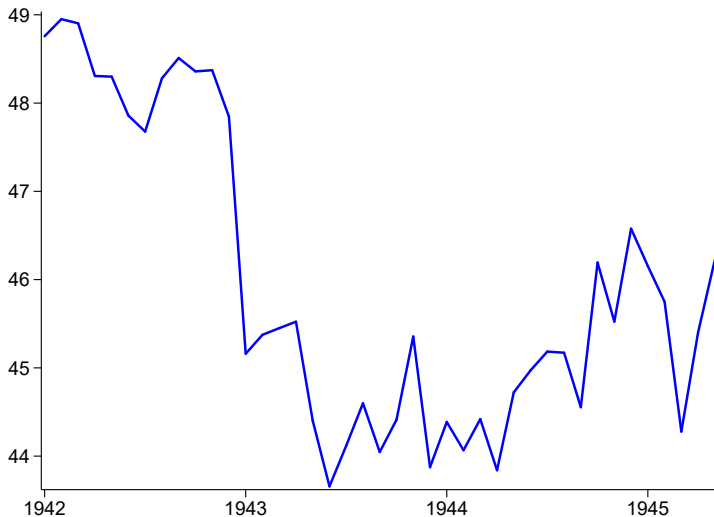


Capital Utilization



Source: AMPR and author's calculation

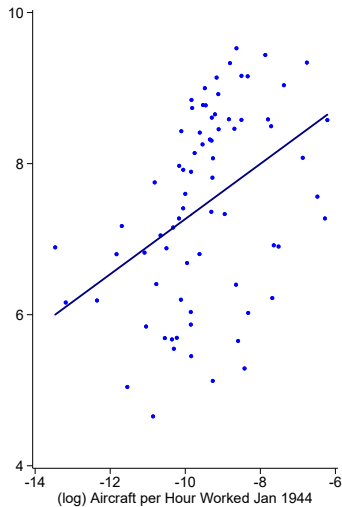
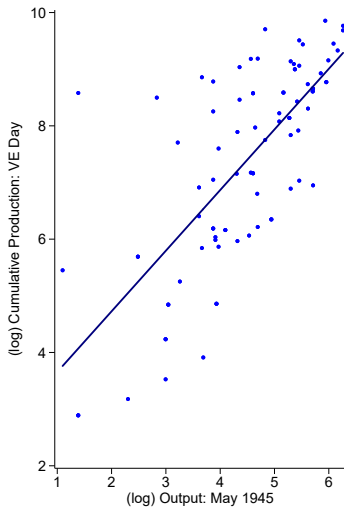
Hours per Worker



Source: AMPR and author's calculation

Learning by Doing with OLS

Autocorrelation in LBD Regressions



Left hand panel: Output is auto-correlated. Strong correlation between current and cumulative output

Right hand panel: "Experience" highly correlated with *past* productivity. Productivity → experience.

Detail

Changes in Procurement Strategy and Identification

Identification Challenge

Aircraft demand endogenous to (expected) plant productivity

- 1) Include time and production line (plant \times model) fixed effects
 - Controls for (constant) differential productivity across plants and models
 - Controls for industry-wide productivity growth and fluctuations
 - Remaining variation: differential time-by-production line productivity changes
 - Concern: gov directs procurement to plants when they are expected to be relatively more productive.
- 2) Control for lagged demand
 - Reflecting “shocks” to demand that couldn’t be predicted by an AR(6).
- 3) Instrument for demand

Broad Aircraft Types

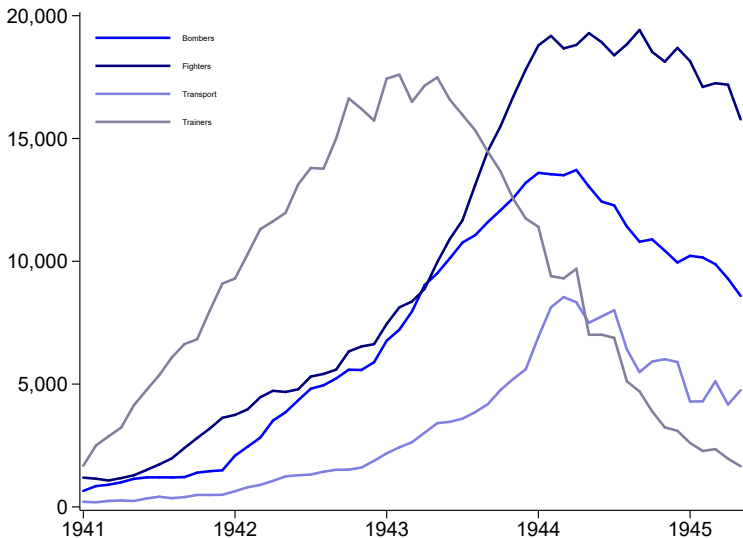
Instrument demand for aircraft from production line mp with the total production of all aircraft in broad category that includes model m , excluding mp itself (“leave one out”)

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



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

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

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)

Results

Specification

Local projection IV, controlling for 6 monthly lags

Include month and production line (plant \times model) fixed effects

First stage:

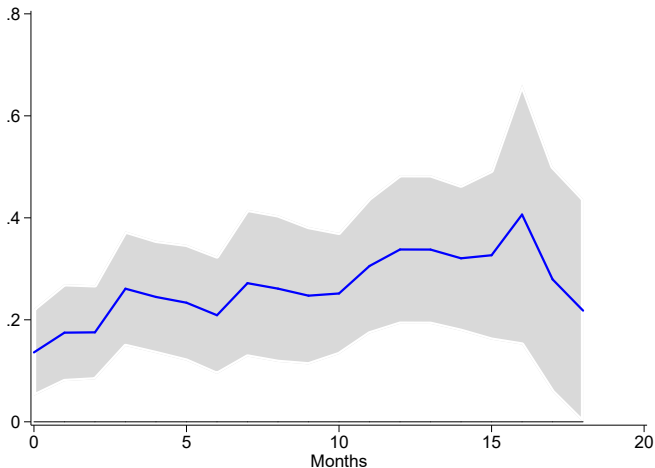
$$D_{mpt}^h = \gamma SS_{mpt} + \text{controls} + \text{FE} + \text{lags} + u_{mpt}$$

IV:

$$y_{mp,t+h} = \beta_h \hat{D}_{mpt} + \sum_{i=1}^I \left(\delta_i^y y_{mp,t-i} + \delta_i^D D_{mpt-i} \right) \\ + \alpha_t + \alpha_{mp} + \text{controls} + \varepsilon_{mpt}$$

D: output; SS: Shift share instrument; y: Productivity (or other) measure

Output per Hour Worked



Local projections. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of dependent variable and output. $\sum_{\tau} Share_{\tau p, 1943} Y_{\tau t}$ instruments for output, where

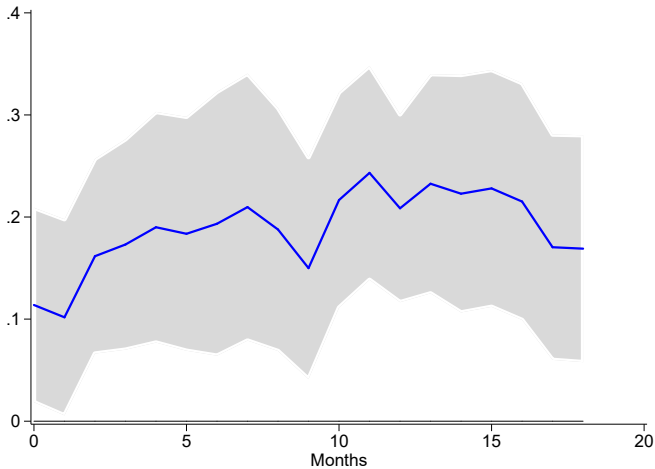
$Share_{\tau p, 1943}$ is the share of aircraft of type τ produced in plant p in Jan 1943.

Pre-Trend

Demand Response

TFP Response

TFP Controlled for Capital Utilization



Pre-Trend

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
4. War Manpower Commission labor market classification

Correlations

Sum Stats

Triple Difference Specification

Investigating channels by interacting production in production line mp in month t with plant characteristic c

1. $c = 1$ if plant p had capital utilization above median at beginning of war (1942)
2. $c = 1$ if plant p had hours per worker above median at beginning of war (1942)... (ect.)

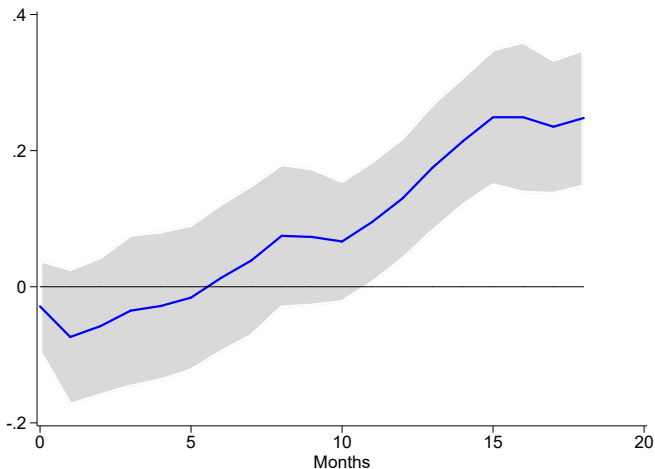
Impulse responses have a $3 \times \text{dif}$ interpretation: relative productivity response to (instrumented) output in plants with high vs. low capacity constraints

IV:

$$y_{mpt+h} = \beta_h^{3D} [\widehat{\text{Output} \times c}]_{mpt} + \omega \widehat{\text{Output}}_{mpt} + \eta \hat{c}_p + \text{lags} + \text{FE} + \varepsilon_{mpt}^{3D}$$

Output per Worker Response to Demand

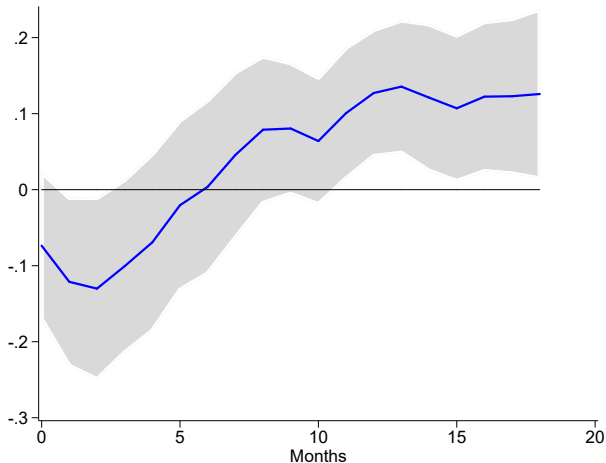
Relative Response in High Capital Utilization Plants



Local projections of output per worker response to 1% increase in production in high capital utilization plants relative to control. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, 6 monthly lags. Pre-Trends Capacity Utilization & Demand

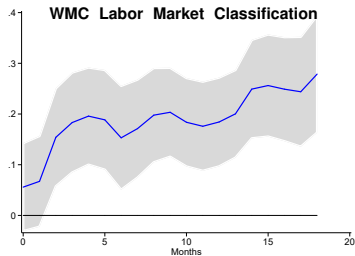
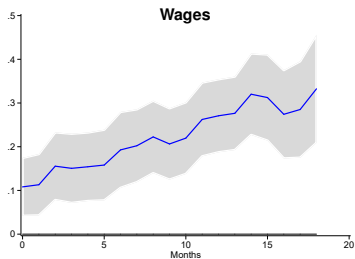
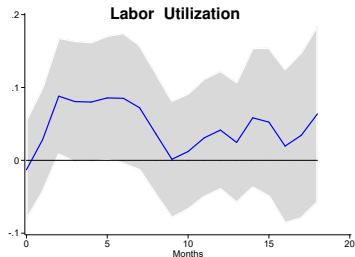
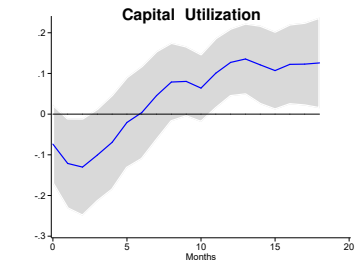
TFP Response to Demand

High vs. Low Capital Utilization Plants



Relative Responses of TFP to Demand

Different Capacity Constraint Metrics



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

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,

poration 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.

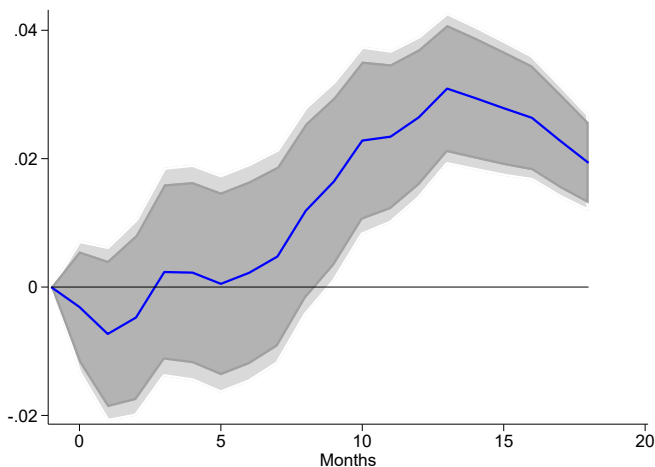
Brooklyn Daily Eagle, Oct 12, 1942

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

Sources

Mass Production Count

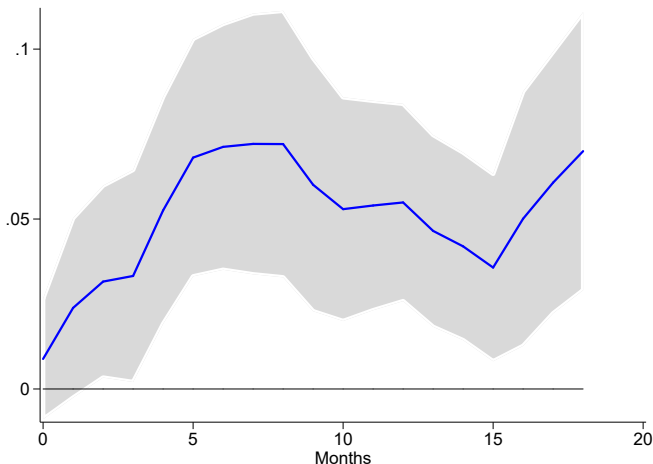
Relative Response in High vs. Low Capital Utilization Plants



Local projections of count of mass production methods introduced (in percentage points) in response to 1% increase in production in high capital utilization plants relative to control. 90% and 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, six monthly lags of demand.

Outsourcing

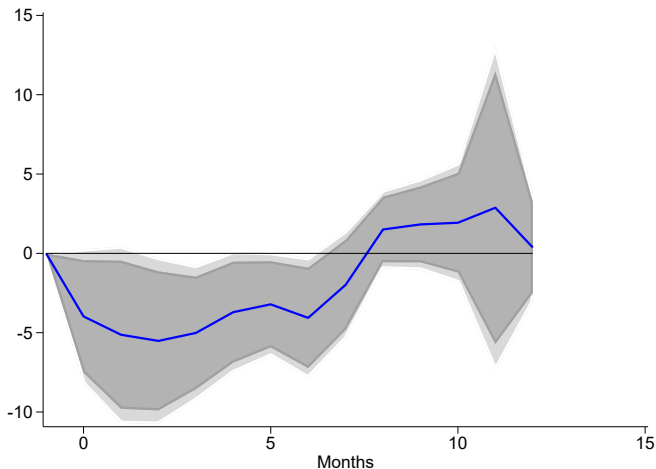
Relative Response in High vs. Low Capital Utilization Plants



Local projections of percent of outside production (in percentage points) in response to 1% increase in production in high capital utilization plants relative to control. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of output.

Absenteeism

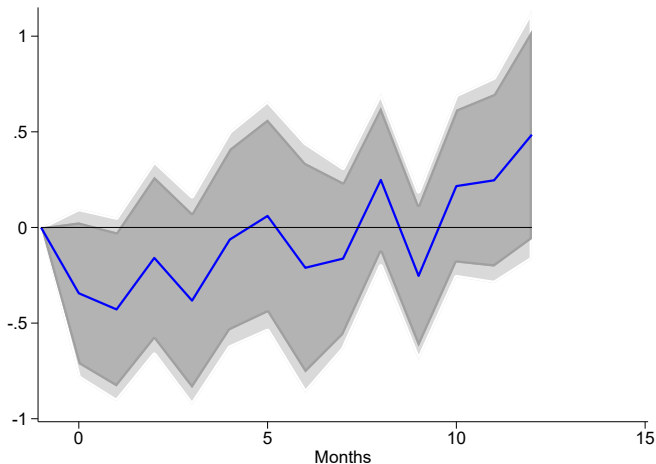
Relative Response in High vs. Low Labor Utilization Plants



Local projections of percent monthly hours lost due to worker absence (in percentage points) in response to 1% increase in production in high capital utilization plants relative to control. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, one lag of demand. **Absenteeism Capital Utilization**

Quit Rate

Relative Response in High vs. Low Labor Utilization Plants



Local projections of percent workers separated due to quits (in percentage points) in response to 1% increase in production in high capital utilization plants relative to control. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, one lag of demand.

Absenteeism Capital Utilization

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.

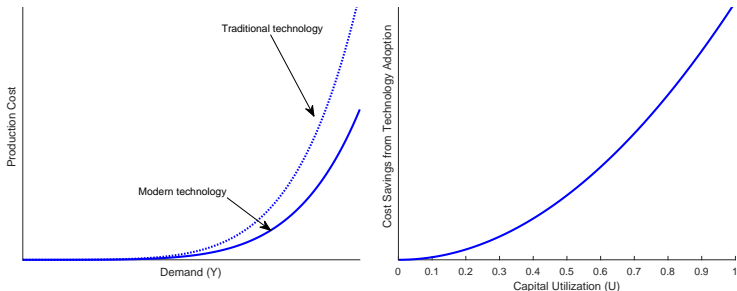
$$z(HL)^\alpha (UK)^{1-\alpha} \geq \bar{Y}$$

FOC:

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

- \Rightarrow equalizing marginal costs of utilization across factors
- Marginal utilization costs increasing in \bar{Y}
- \Rightarrow Value of technology adoption increasing in \bar{Y} and U

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

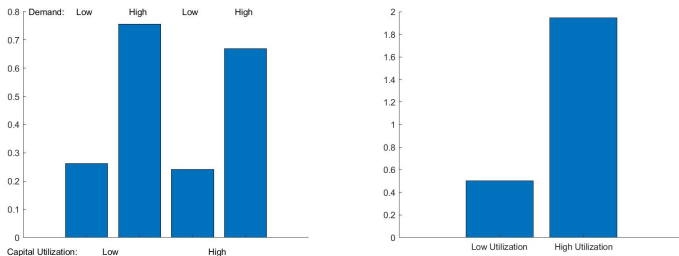
Can now simulate the theoretical equivalent of triple difference:

- 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

Wrapping Up

Contribution

Causal evidence of demand \rightarrow Productivity

- When resources are scarce, plants meet $\frac{1}{5}$ 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)
- 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)

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); 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 (1966); von Weizsacker (1966); Shell (1967); Romer (1987); Newell et al (1999); Popp (2002); Acemoglu & Restrepo (2018)

The LBD and Progress Curve Literature

Eyeballing the raw data shows virtually every production line becomes more productive over time

Existing literature runs the regression:

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

y: output per hour, p: plant, t: month, m: model

[Return](#)

Problems with OLS LBD Regressions

Problem 1 Reverse causation: output caused by productivity

$$Y_t = y_t h_t$$

Problem 2 Productivity is auto-correlated: Experience and current productivity both correlated with past productivity

$$\text{CumOutput}_{mpt} \equiv \sum_{s=0}^t \text{Output}_{mps} \equiv \sum_{s=0}^t y_{mps} h_{mps}$$

$$E(\varepsilon_{mpt} \sum_{s=0}^t y_{mps} h_{mps}) \neq 0$$

Problem 3: Much of the labor productivity increase is due to massive capital accumulation

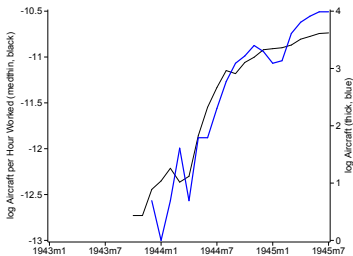
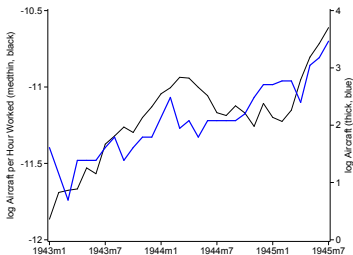
Y: output, y: output per hour, h: hours, p: plant, t: month, m: model

[Return](#)

C-54 Production in Two Douglas Aircraft Plants

Santa Monica (top); Chicago (bottom)

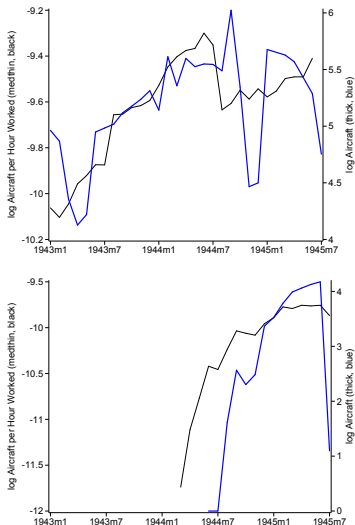
Shifting production to
new plant within firm
→ productivity decline
→ lower output



Two Models in Convair's San Diego Plant

B-24 (top); PB4Y (bottom)

Shifting production to new product within plant → productivity decline & lower output



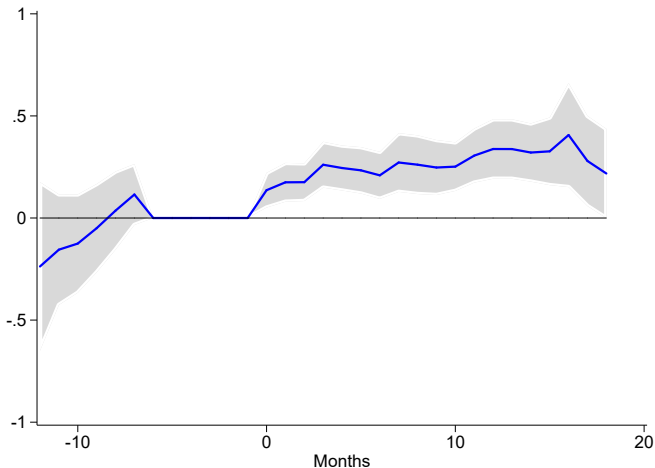
LBD By OLS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cum Y	0.382*** (.011)	0.406*** (.011)	0.322*** (.003)	0.294*** (.005)	0.326*** (.009)		0.278*** (.010)	0.014 (.011)
Current Y						0.268*** (.007)	0.0574*** (.009)	0.0426*** (.005)
[1em] Time FE		X		X	X	X	X	X
Plant FE			X	X				
Plant*Model FE					X	X	X	X
Lagged y								X
Observations	2553	2553	2553	2553	2553	2491	2491	1906

Standard errors in parentheses

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

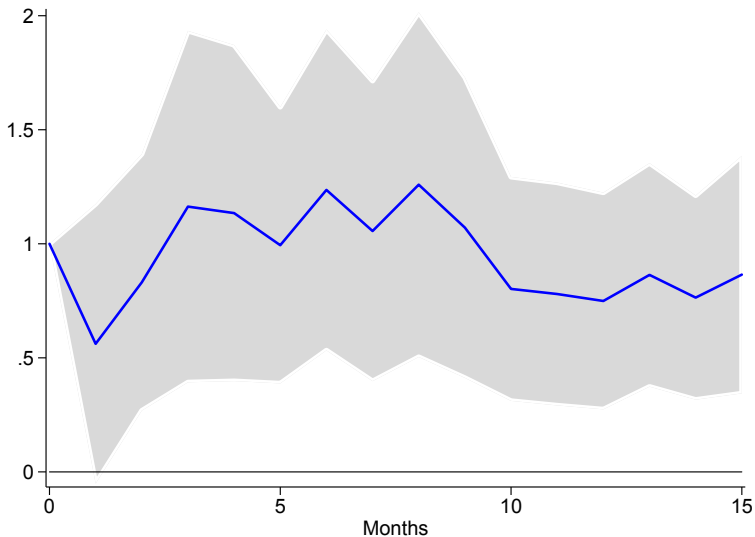
Pre-Trend in Output Per Worker



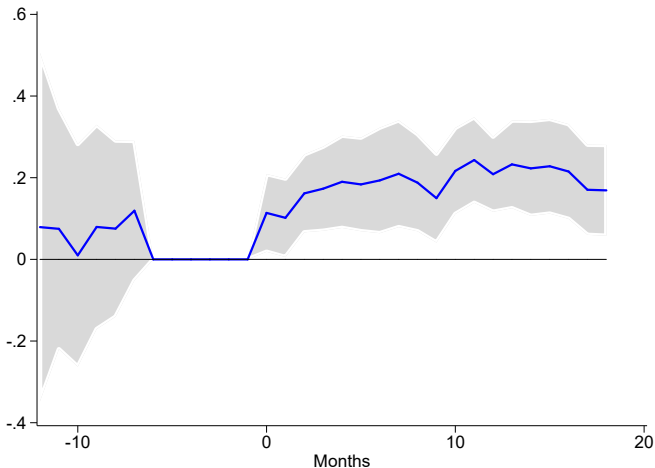
Local projections of output per worker response to 1% increase in demand. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of dependent variable and output.

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Output's Own Response to Demand



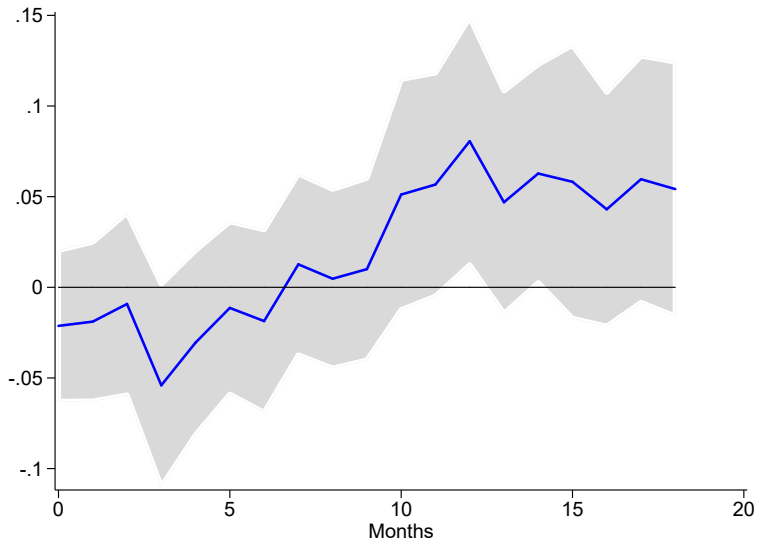
Pre-Trend in TFP



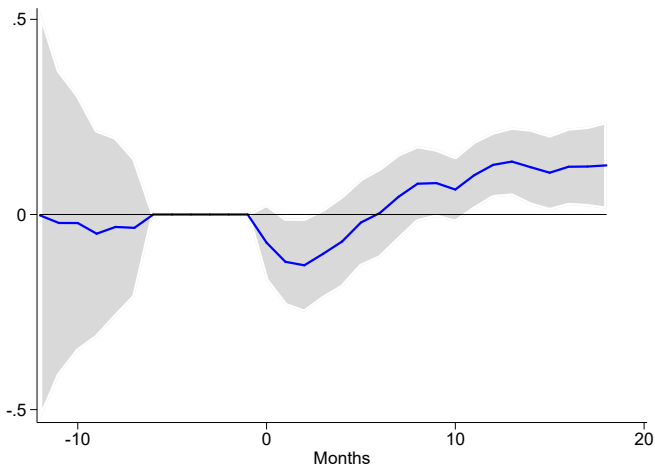
Local projections of output per worker response to 1% increase in demand. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of dependent variable and output.

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Capital Utilization Response to Demand



Pre-Trend in 3×D Regression



Local projections of TFP response to 1% increase in production in high capital utilization plants relative to control. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, 6 monthly lags.

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Capacity Utilization and Demand

Despite enormous concern 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

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	0.47***	1		
Wages	0.11	0.11	1	
Labor market priority	0.29*	0.10	0.42***	1

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

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Who Were the Constrained Plants?

	Capital Utilization		Wages	
	Low	High	Low	High
$\Delta\%$ Output per Worker	127	104	117	103
Firm Age (Months)	175	195	181	193
Plant Age (Months)	60	139***	106	108
Hours per Pound	4.61	3.06	3.69	3.32
Airplanes Produced	43.9	80.8	81.7	58.9
Unit Cost (000's \$)	113	111	93	129
Wing Span (Meters)	21.4	20.05	20.9	20.1
Public Plant Financing (mln \$)	20.8	15.7	21.3	14.0*

Averages in January 1943, except for plant financing (January 1945).

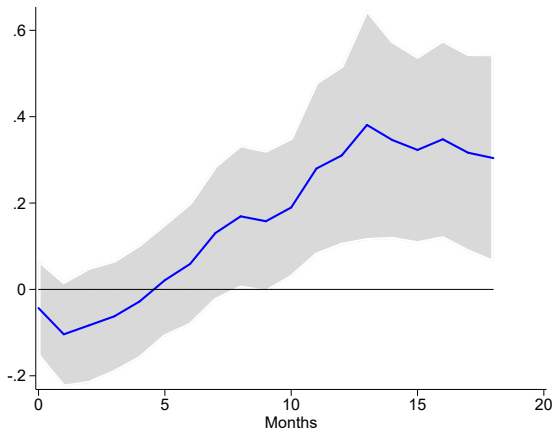
Changes from January 1943 to January 1945

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

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Capital Utilization, Demand, and Productivity Growth

Controlling for plant age and “Old Plant” \times demand



Local projections of output per worker response to 1% increase in production in above median capacity utilization plants relative to control. Controlling for plant age and plant age interacted with demand. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, 6 monthly lags. [Back](#)

Production Methods

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

Craven and Cate vol. 6, 1955

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.

Taylor and Wright, 1947

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.

Lilley et al, 1947

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.

Taylor and Wright, 1947

News Sources for Mass Production Methods

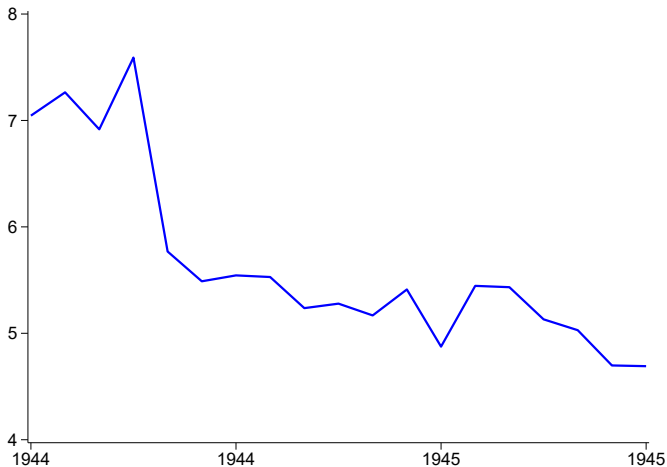
Sources

- 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

Absenteeism: Time Series

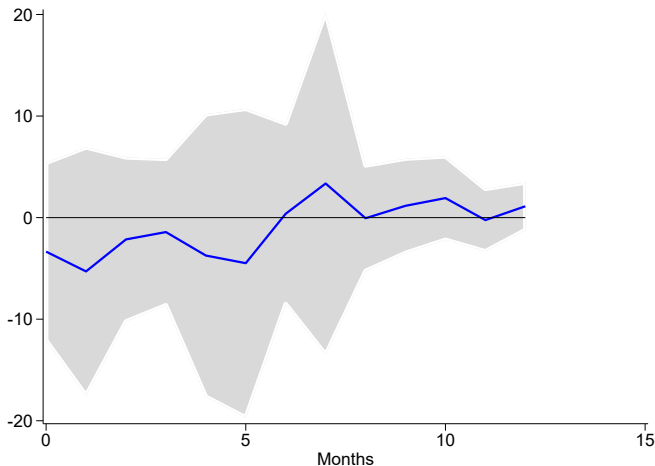


Percent hours lost due to worker absenteeism. Monthly average accros plants.

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Relative Response to Demand

Absenteeism in High vs. Low Capital Utilization Plants



Local projections of percent of outside production (in percentage points) in response to 1% increase in production in high capital utilization plants relative to control. 95% confidence intervals in gray. Includes month and plant \times model (production line) fixed effects, 6 monthly lags of dependent variable and output. [Back](#)

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

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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):

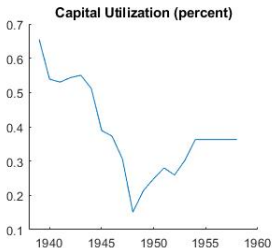
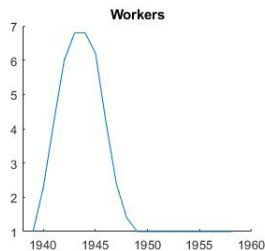
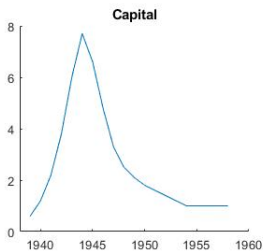
Parameter/Target	Value	Source
d	0.08	Literature
r	0.03	Post war data
$\bar{H} = FT$	0.24	40 hour workweek
ω	0.5	Typical overtime rates
$\frac{W}{wFT}$	0.25	Typical overhead
U	0.36	$1\frac{1}{2}$ daily shifts, 5 days a week
α	$\frac{2}{3}$	Post-war labor share

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

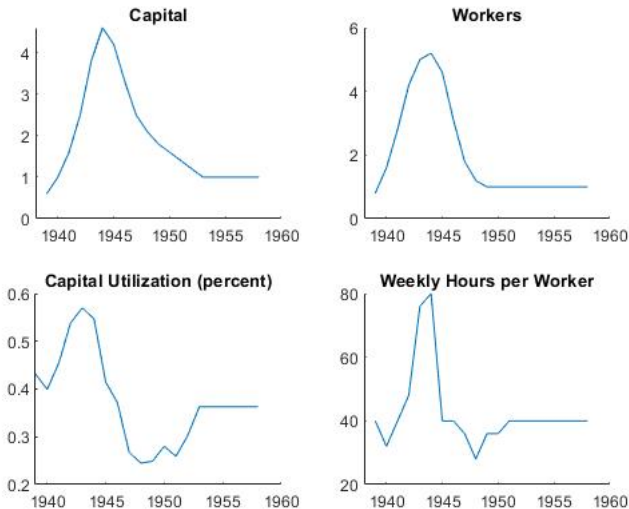
Hit plant with unanticipated (“MIT”) World War II shock to demand starting in 1938 [Back](#)



Simulation: Low Demand

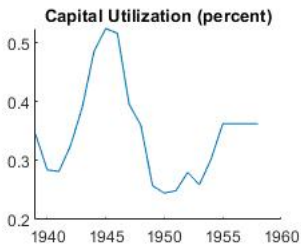
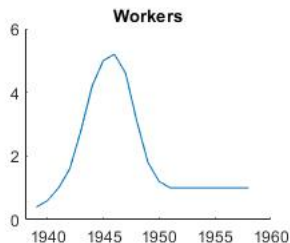
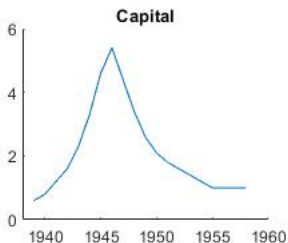
Scale shock to plant at 25 percentile of demand [Back](#)

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 [Back](#)



“Experiment”

Average firm saw 33% productivity increase

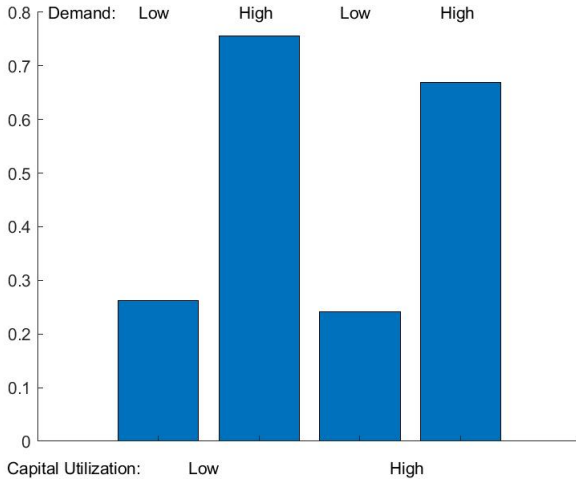
Simulate cost reduction from technology adoption that increases z from 75% of post-war TFP to post-war TFP

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

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Cost Savings from Technology Adoption



Relative Cost Savings from Tech Adoption

