# Machines and Machinists: Incremental Technical Change and Wage Inequality

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# Motivation

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1. Wage inequality in past decades
2. Technological revolutions

# Weaver productivity across countries and over time

In 1910 one New England cotton textile operative performed as much work as 1.5 British, 2.3 German, and nearly 6 Greek, Japanese, Indian, or Chinese workers. (Clark, 1987)

A typical weaver in the United States in 1902 produced over *50 times* as many yards of cloth in an hour of weaving as did a weaver a century earlier producing a comparable cloth. (Bessen, 2012)

# Not all of it is *quantity* of capital

The weaver in 1902, however, achieved that output using *eighteen* power-driven looms while the weaver of 1802 used a single handloom. (Bessen, 2012)

On technical performance, there was a small but significant quality gap in favour of the imported [rather than Indian] machine. (Sutton, 2001)

# Outline

# An engineering model of machines and machinists

# Standard model

$$Y = K^{\alpha} L^{1-\alpha}$$

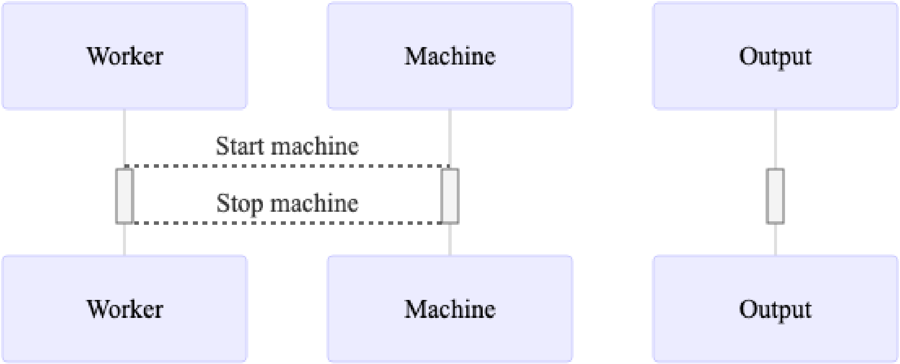
# How do machines and people work together?

**Tool model** A worker feeds material into a metal press (both worker and machine busy) to produce.

**Operator model** A power loom produces in an autonomous fashion (worker idle), until a problem arises. The operator fixes it (machine idle) to get it back to work as fast as possible.

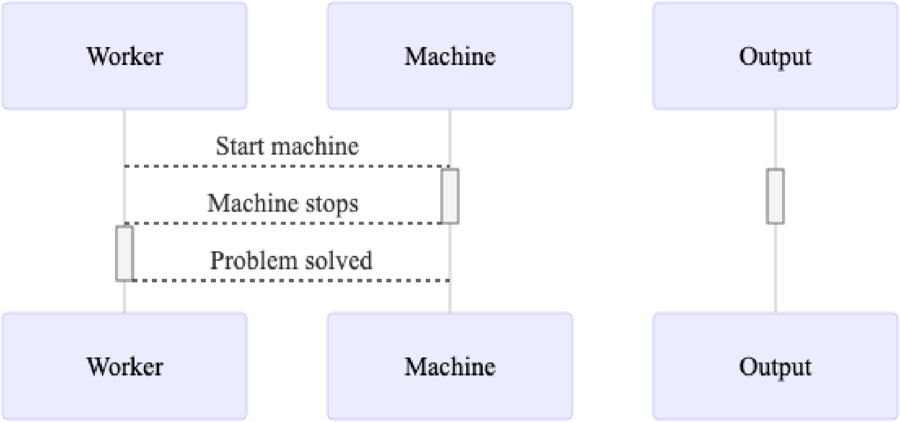
This paper studies the *operator model*.

# Tool model



Worker
Machine
Output
Start machine
Stop machine
Worker
Machine
Output

# Operator model



# Two measures of quality

machine quality Expected autonomous uptime $\theta$
worker quality Speed of fixing problems $h$

Machine busy for $\theta$, idle for $1/h$.

Expected fraction of time working : $\theta h/(1+\theta h) \equiv x$.

Worker busy $(1-x)$ fraction of the time.

# Appendix

# Worker wages

Workers earn $w$ in agriculture. Large $L$ number of workers, few $K$ machines.

# Net output over agriculture

$$x - w(1 - x) = x(1 + w) - w$$

# Equilibrium

$$K(1 - x) \leq L$$

# Output per worker hour

$$\frac{xK_i}{L_i} = \frac{x}{1-x}$$

# Output per worker hour

output_per_hour.png

# Return to machine quality

$$\frac{\partial Q}{\partial \theta} = x(1-x)(1+w)$$

# Return to machine quality

return_to_theta.png

# Value of a machine

$$Q_i - wL_i = x(1 + w) - w$$

# Value of a machine

value_of_machine.png

# Innovation

# Two types of innovation

1. Improve quality $\theta$
2. Build more machines $K$

Suppose both cost the same amount of final goods.

# Three epochs of innovation

1. Artisanal period. Labor is slack, wages are determined in agriculture. Improving machine quality has higher return. $x(1-x)(1+w) > x(1+w) - w$. $x$ continues to increase.
2. Mass production. Value of a machine is high enough to produce more. $K/L$ increases with constant $x$.
3. Automation. After all $L$ has been absorbed from agriculture, wages start to rise. The returns to labor-saving machine quality improvement now exceed the value of an old machine. $x$ keeps increasing.

# Plus one

4. Singularity (never reached). As $x \to 1$, the ratio of machine time to worker time grows without bound. Nobody works, all work is done by robots. But to reach this state from a very large degree of automation (say, $x = 0.999$), labor has to capture almost all of the output, otherwise there is no incentive to innovate further.

# Artisanal period

$$\frac{w}{1+w} \leq x \leq \sqrt{\frac{w}{1+w}}$$

# Production function

# Production function

$$Q_{it} = \Omega_{it}(\lambda K_{it}^F + K_{it}^D)^\alpha L_{it}^\beta M_{it}^\gamma$$

with $\lambda > 1$

$$q_{it} \approx \omega_{it} + \alpha k_{it} + \beta l_{it} + \gamma m_{it} + \alpha(\lambda - 1)\frac{K_{it}^F}{K_{it}}$$

# Patterns of capital imports

# Data

- Hungarian Customs Statistics, 1992–2003
  - all *direct* exporter and importer
  - detailed by product (HS6): capital goods
  - and country of origin
- Balance Sheet and Earnings Statement
  - revenue, employment, material cost
  - capital: book value of equipment

# Stocks and flows

- Imports are flows, equipment value is stock.
- Gross investment *flow*:

$$\hat{I}_{it} = K_{it} - (1 - \delta_{it}) K_{i,t-1}$$

  with $\hat{I}_{it} = \hat{I}^D_{it} + I^F_{it}$
- Imported equipment *stock*:

$$\hat{K}^F_{it} = (1 - \hat{\delta}_{it}) \hat{K}^F_{i,t-1} + I^F_{it}$$

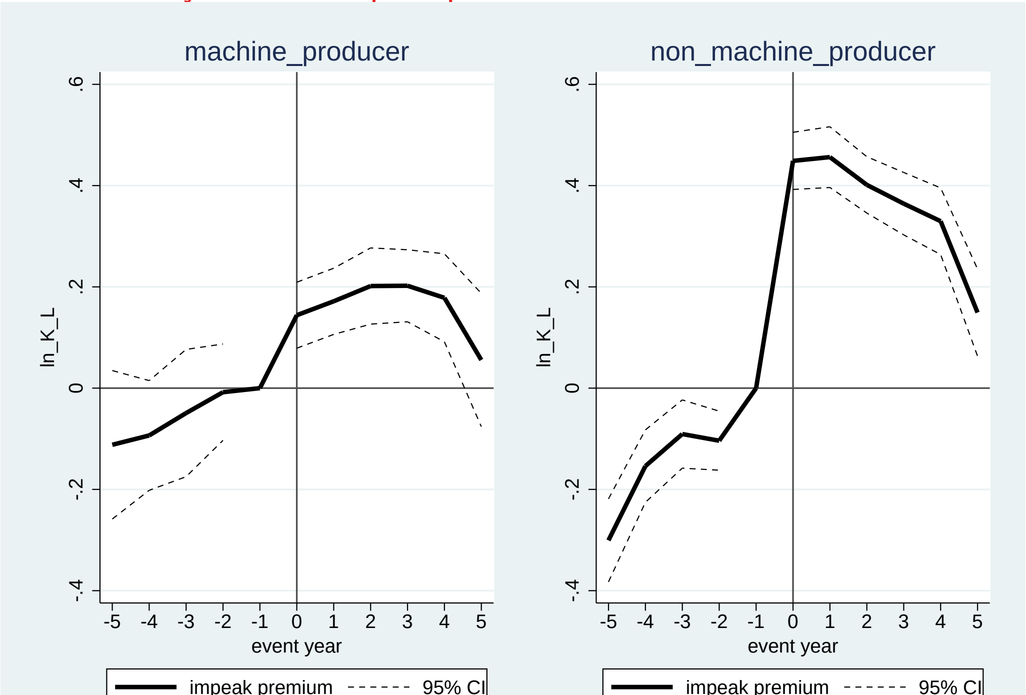
- Complications: what if $I^F_{it} > I_{it}$?

# Distribution of investment rates (following Khan and Thomas, 2008)

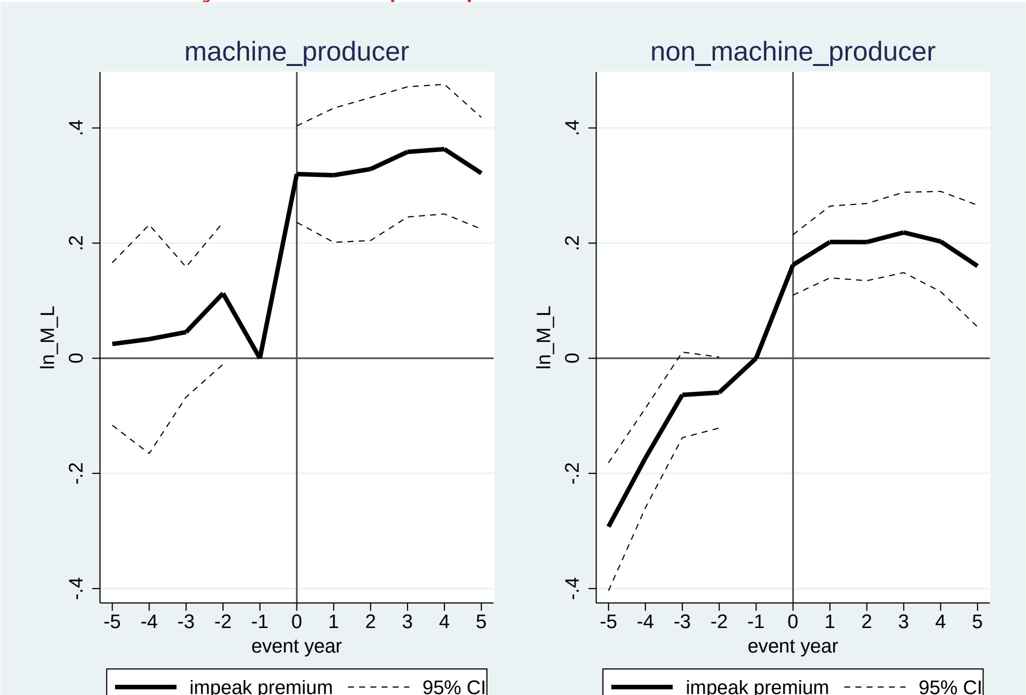
| | Manufacturing 10+ employees | Non-machine manuf 10+ employees | Non-machine manuf all firm sizes |
|---|---|---|---|
| Average IR | 0.321 | 0.270 | -0.132 |
| Average IR (winsor. 0.01) | 0.378 | 0.335 | 0.338 |
| Median IR | 0.291 | 0.260 | 0.247 |
| Inaction (%) | 5.9 | 6.4 | 13.3 |
| Positive investment (%) | 85.9 | 85.0 | 77.0 |
| Negative investment (%) | 8.1 | 8.6 | 9.8 |
| Positive spike (%) | 59.9 | 56.9 | 54.1 |
| Negative spike (%) | 3.7 | 3.8 | 5.1 |
| Observations | 75,281 | 57,607 | 137,508 |

Notes: Inaction: abs(IR)<0.01, Positive spike: IR>0.2, Negative spike: IR<-0.2.
All samples exclude the first year of firms, where $I_t$ equals $K_t$ by construction.

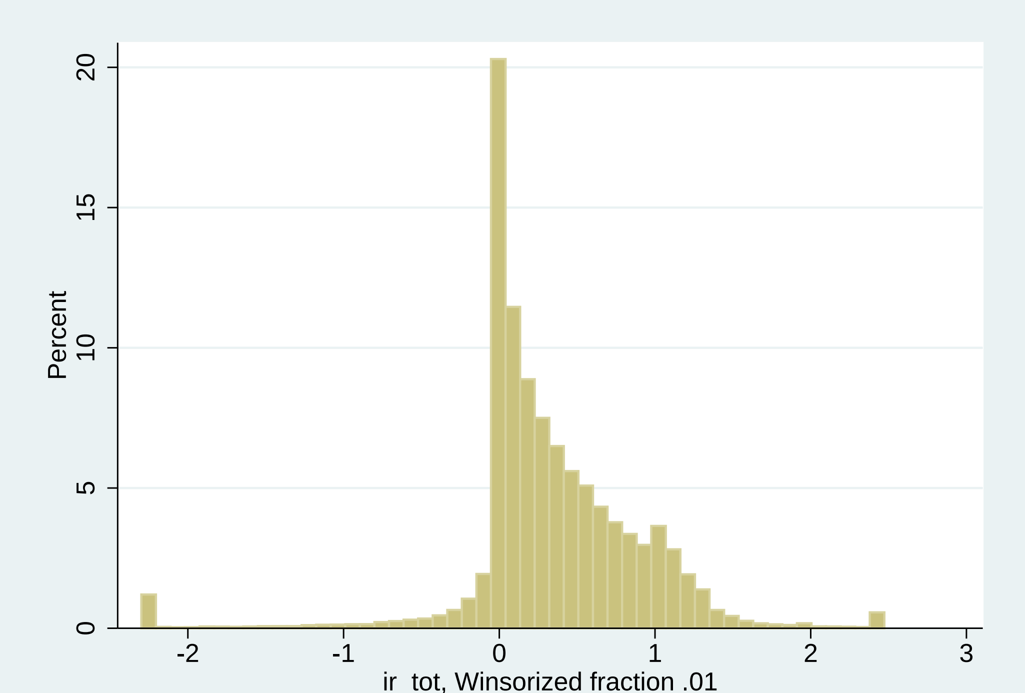
# Capital intensity around import peaks



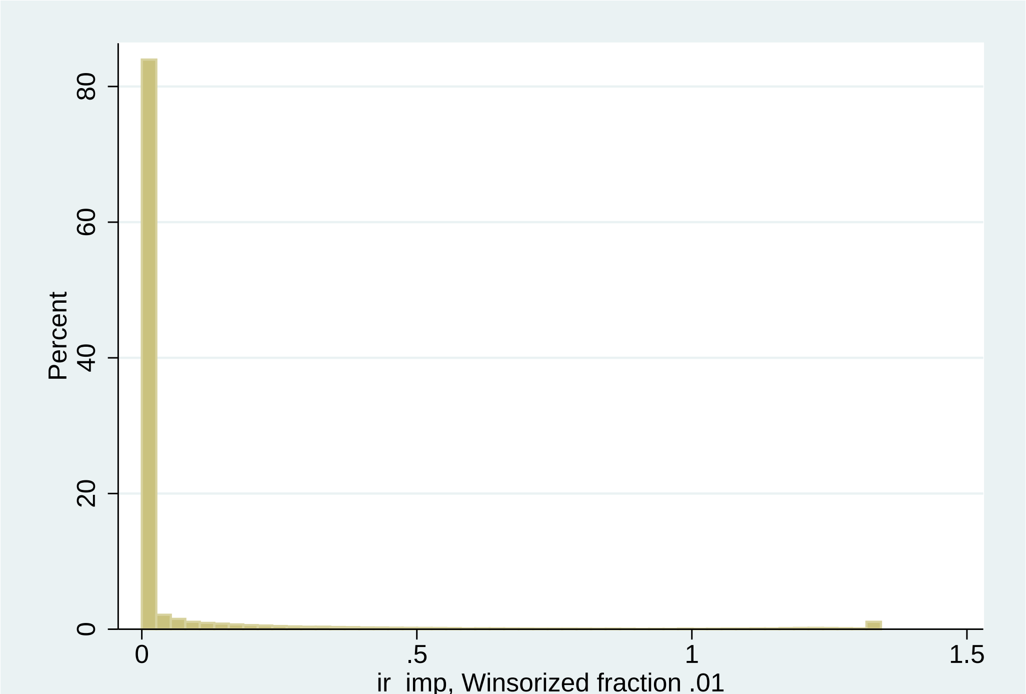
# Material intensity around import peaks



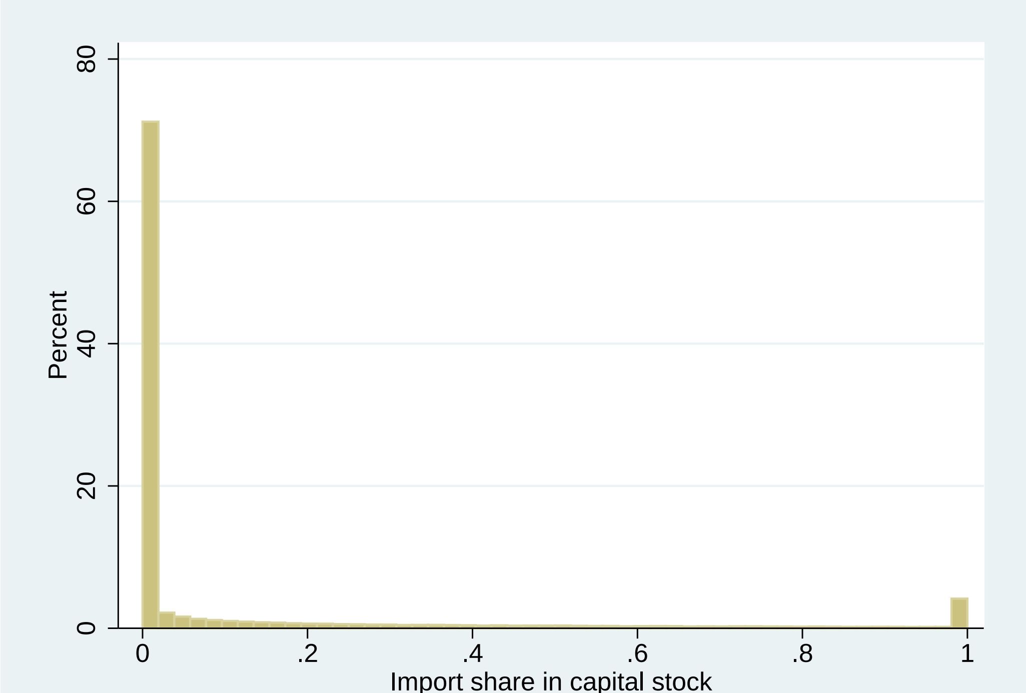
# Investment rate distribution



# Imported investment rate distribution

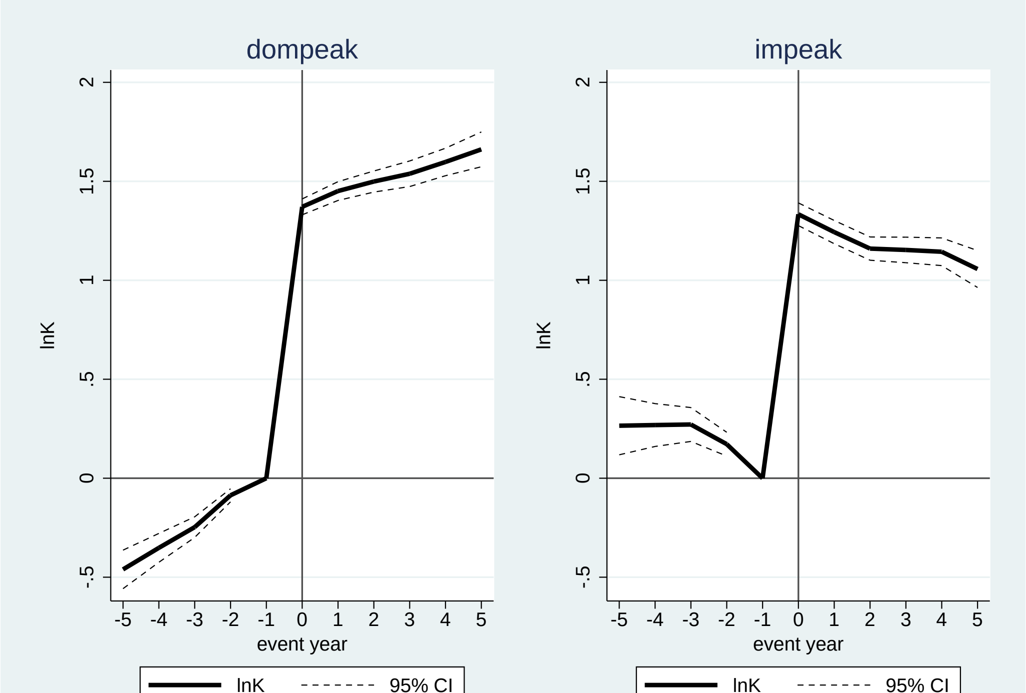


# Import share in capital sock

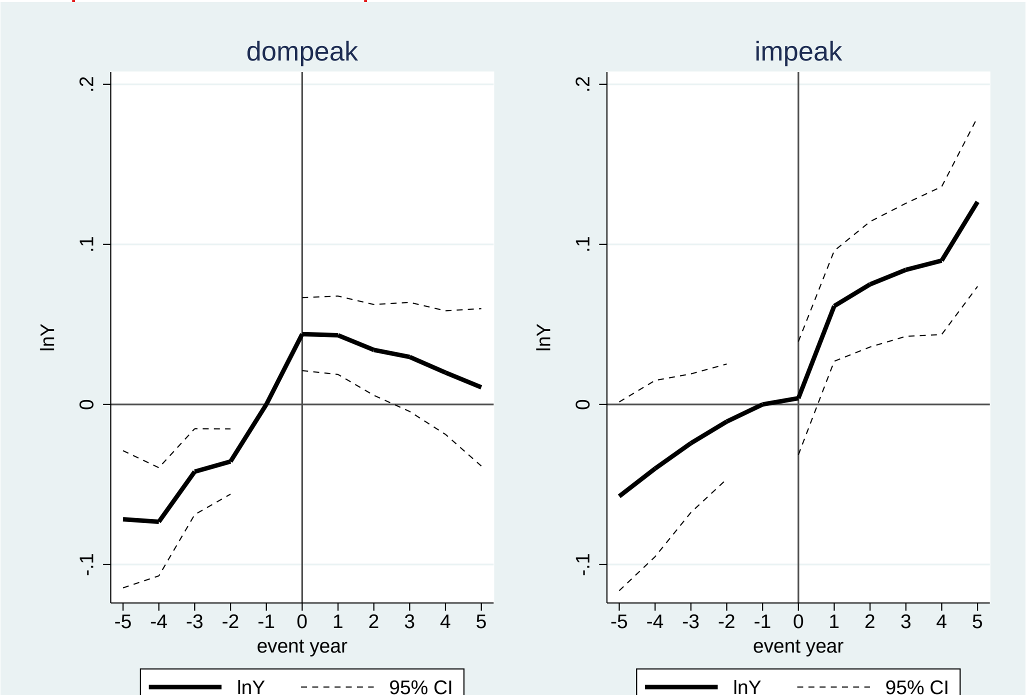


# Event studies around large investments

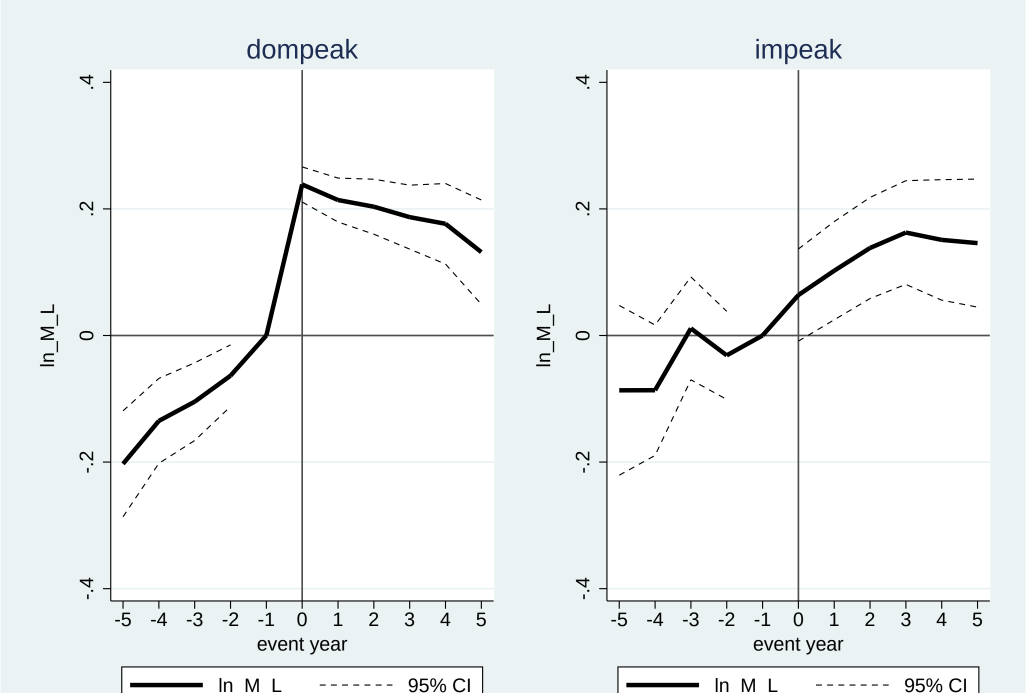
# Capital stock increases by same amount (by construction)



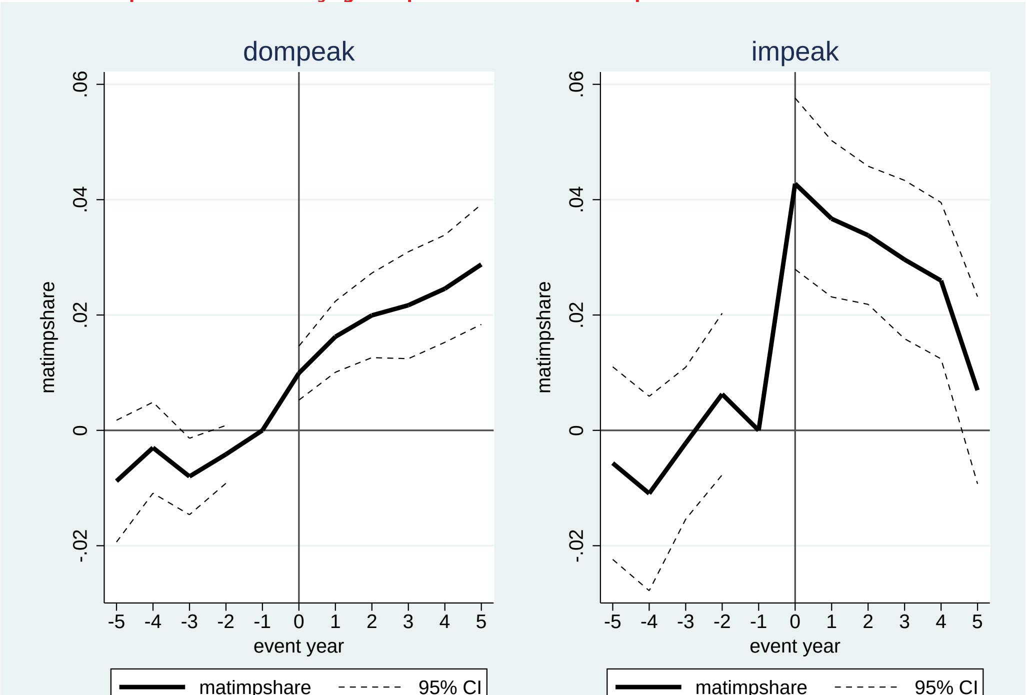
# TFP improves more for imported investment



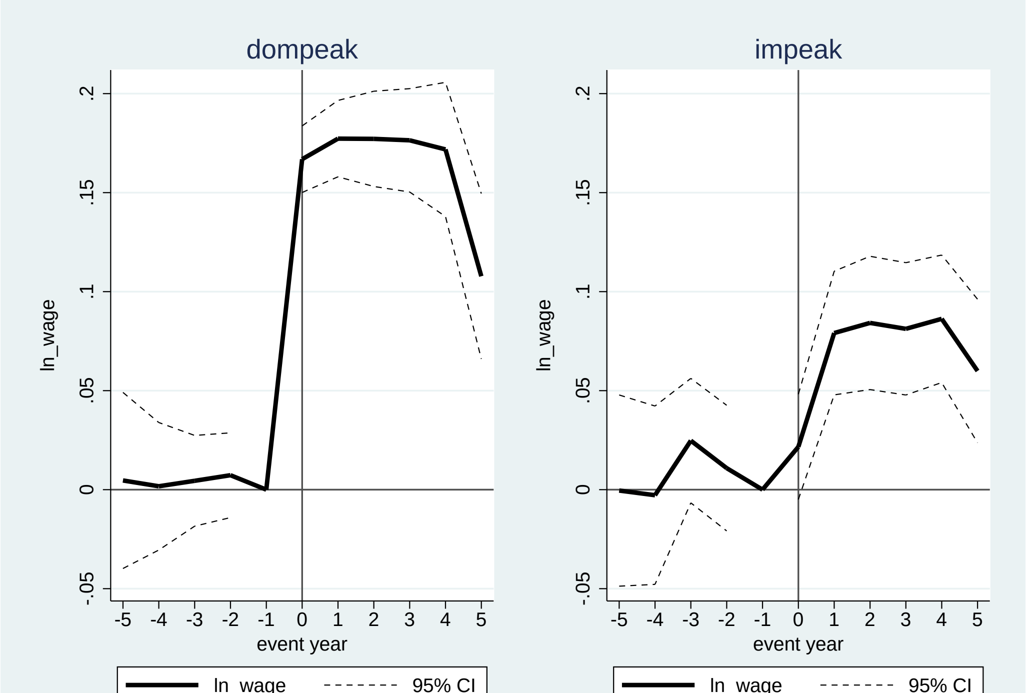
# Material intensity increases for both types of investment



# Material import intensity jumps more for imported investment

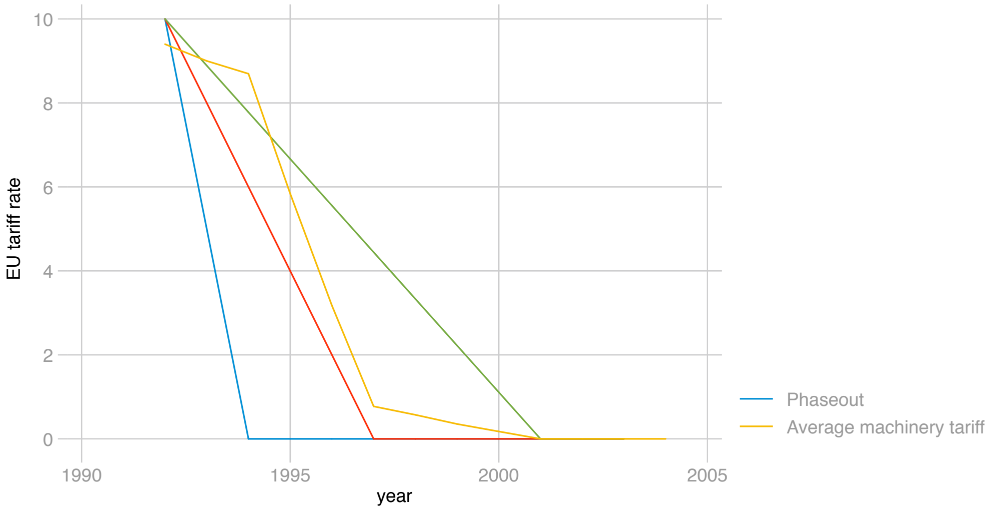


# Average wage reacts to domestic investment

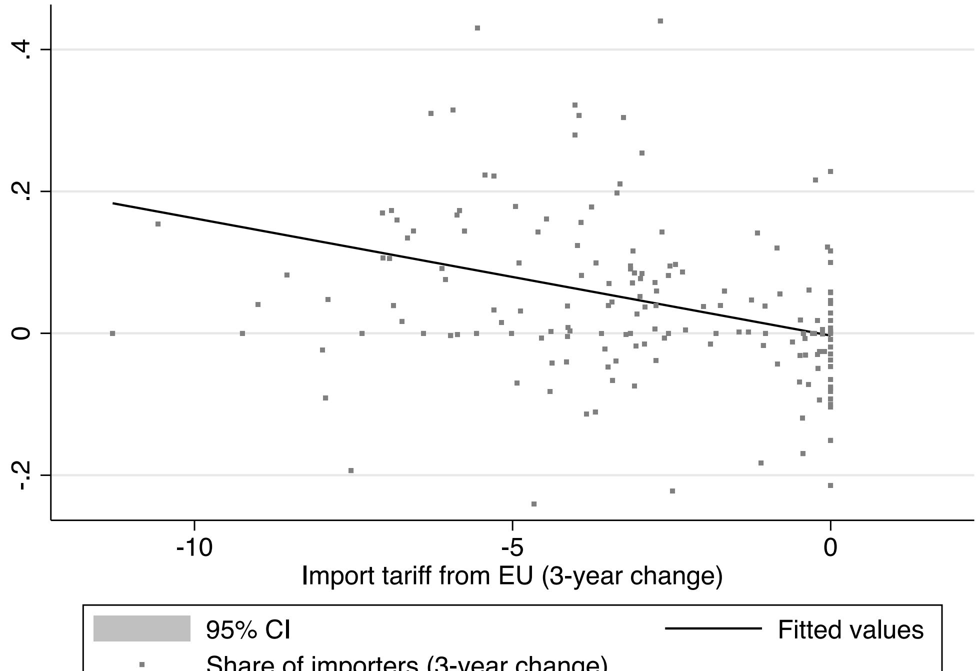


# Identification

# Interim Agreement with EEA (1991) phased out tariffs



# Faster phaseout results in faster imports (Koren, Csillag and Köllő, 2019)



# When do firms import?

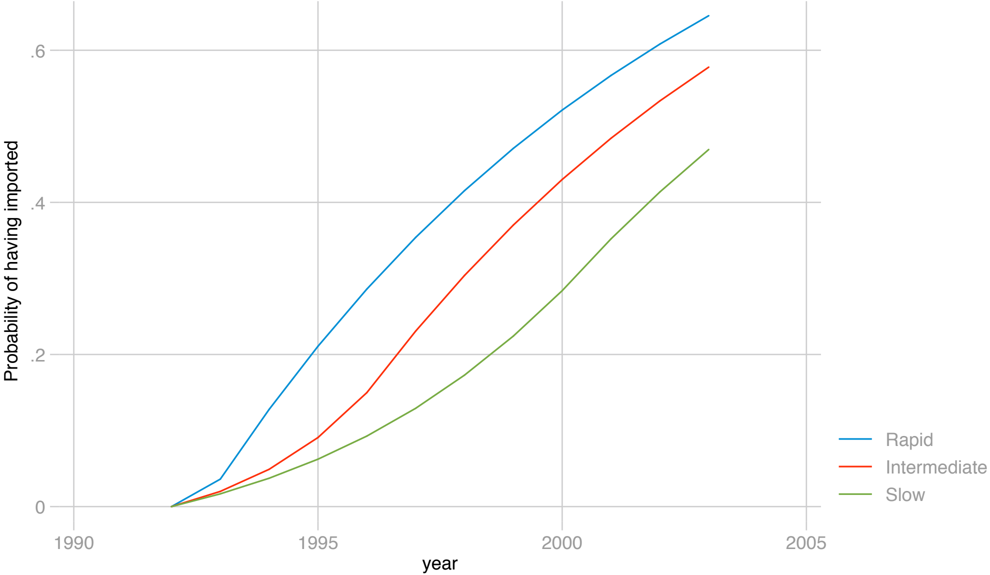
- Lumpy imported investment suggests fixed cost of importing (also see Halpern, Koren and Szeidl, 2015)
- Import if $p_t^F/p_t^D < f(L_{it})$.
- Hazard of *starting to import* (flow):

$$\Pr(K_{it}^F > 0 | K_{i,t-1}^F = 0) = \mu_{st} - \xi \Delta \tau_{st} L_{it}$$

- Probability of *having imported* in the past (stock):

$$\Pr(K_{it}^F > 0) \approx \tilde{\mu}_{st} - \xi L_{it-\mathsf{age}_{it}} \sum_{a=0}^{\mathsf{age}_{it}} \Delta \tau_{st-a}$$

# Example of cumulated import hazards



# Results

# First stage

| Depvar: having imported (dummy) | Pooled | Firm FE |
|---|---|---|
| cdtariffeu X size 0-10 | -0.017*** | 0.009* |
| | (0.001) | (0.005) |
| cdtariffeu X size 10-50 | -0.026*** | -0.001 |
| | (0.001) | (0.005) |
| cdtariffeu X size 50+ | -0.046*** | -0.019*** |
| | (0.002) | (0.005) |
| lnK | 0.048*** | 0.027*** |
| | (0.002) | (0.001) |
| lnM | 0.018*** | 0.007*** |
| | (0.001) | (0.001) |
| lnL | 0.008** | 0.018*** |
| | (0.003) | (0.003) |
| foreign (dummy) | 0.321*** | 0.149*** |
| | (0.011) | (0.022) |
| size dummies | yes | yes |
| age dummies | yes | yes |
| industry x year effects | yes | |
| year effects | | yes |
| Observations | 102,516 | 102,516 |
| R-squared | 0.296 | 0.211 |
| Number of id | | 17,736 |
| F-test | 239.1 | 91.74 |

Notes: Robust standard errors (clustered by industry) are in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

# Productivity

| Depvar: lnY | Pooled | | Firm FE | |
|---|---|---|---|---|
| | OLS | IV | OLS | IV |
| having imported (dummy) | 0.199*** | 0.263*** | 0.086*** | 0.781*** |
| | (0.015) | (0.075) | (0.012) | (0.112) |
| lnK | 0.132*** | 0.129*** | 0.092*** | 0.073*** |
| | (0.005) | (0.006) | (0.004) | (0.005) |
| lnM | 0.413*** | 0.412*** | 0.297*** | 0.292*** |
| | (0.009) | (0.010) | (0.010) | (0.010) |
| lnL | 0.299*** | 0.299*** | 0.364*** | 0.353*** |
| | (0.010) | (0.010) | (0.010) | (0.010) |
| foreign (dummy) | 0.161*** | 0.140*** | 0.091** | -0.033 |
| | (0.023) | (0.034) | (0.043) | (0.047) |
| size dummies | yes | yes | yes | yes |
| age dummies | yes | yes | yes | yes |
| industry x year effects | yes | yes | | |
| year effects | | | yes | yes |
| Observations | 102,516 | 102,516 | 102,516 | 102,516 |
| R-squared | 0.771 | 0.771 | 0.545 | 0.503 |
| Number of id | | | 17,736 | 17,736 |

Notes: Robust standard errors (clustered by industry) are in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

# Complementarity

# Complementarity

- Are imported machines complementary with other inputs?
- If so, can explain
  - large gaps
  - divergence
- Two ways to measure complementarity (Brynjolfsson and Milgrom, 2013):
  - performance: $f_{xy} > 0$
  - behavior: $\partial x / \partial y > 0$

# Positive cross derivative of output (Koren, Csillag and Köllő, 2019)

Table 4: The effect of machine type and worker quality on log output per machine

| | (1)<br>Production function |
|---|---|
| Log number of weavers | 0.109*** |
| | (0.029) |
| New machine | -0.858** |
| | (0.335) |
| Log residual wage (as of 1989) of workers at the machine type | -9.91** |
| | (4.62) |
| New machine × log residual wage | 38.53*** |
| | (7.55) |
| Number of observations | 261 |
| $R^2$ | 0.733 |
| Effect of the new machine at 25th percentile of the 1989 residual wage | -0.747 |
| Effect of the new machine at 50th percentile of the 1989 residual wage | 1.20 |
| Effect of the new machine at 75th percentile of the 1989 residual wage | 1.47 |

Notes: Dependent variable: log output per machine. Sample: machine-months for five types of loom. Estimation: OLS. The average residual wage was measured by regressing individual log annual earnings (based on payment by results) in 1989 on age, age squared and type of machine fixed effects, and averaging the residual for workers employed at the given type of machine in the given month. Output is measured in million

# Assortative assignment (Koren, Csillag and Köllő, 2019)

Table 2: The effect of worker quality on the probability that a worker was matched to a new machine

| | (1) |
| --- | --- |
| | Machine-worker assignment |
| Log residual wage in 1989 | 2.63*** |
| | (0.645) |
| Age | 0.231** |
| | (0.100) |
| Age squared | -0.004*** |
| | (0.001) |
| Tenure (years) | 0.051*** |
| | (0.015) |
| Number of observations | 519 |
| Pseudo-$R^2$ | 0.233 |
| Standard deviation of the residual wage | 0.128 |
| Mean dependent variable | 0.299 |

Notes: Dependent variable: 1 if the worker is assigned to a new machine, and 0 otherwise. Sample: person-years for continuing workers employed in the plant in 1989. Estimation: Probit. The residual wage was measured by regressing log payments by results in 1989 on age, age squared and type of machine fixed effects. Standard errors (in parentheses) are calculated from a 200-repetition bootstrap. Coefficients significantly different from zero at 1, 5 and 10 percent are marked by

# Imported machines are more material intensive

| Depvar: ln M/L | Pooled | | Firm FE | |
| --- | --- | --- | --- | --- |
| | OLS | IV | OLS | IV |
| having imported (dummy) | 0.542*** | 0.706*** | 0.206*** | 1.218*** |
| | (0.021) | (0.119) | (0.020) | (0.185) |
| foreign (dummy) | -0.032 | -0.091* | 0.109 | -0.072 |
| | (0.037) | (0.055) | (0.073) | (0.078) |
| size dummies | yes | yes | yes | yes |
| age dummies | yes | yes | yes | yes |
| industry x year effects | yes | yes | | |
| year effects | | | yes | yes |
| Observations | 102,516 | 102,516 | 102,516 | 102,516 |
| R-squared | 0.161 | 0.159 | 0.056 | 0.007 |
| Number of id | | | 17,736 | 17,736 |

Notes: Robust standard errors (clustered by industry) are in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

# Imported machines are more *imported* material intensive

| Depvar: matimpshare | Pooled | | Firm FE | |
|---|---|---|---|---|
| | OLS | IV | OLS | IV |
| having imported (dummy) | 0.127*** | 0.110*** | 0.042*** | 0.148*** |
| | (0.005) | (0.026) | (0.004) | (0.034) |
| foreign (dummy) | 0.138*** | 0.144*** | 0.032** | 0.014 |
| | (0.009) | (0.013) | (0.014) | (0.015) |
| size dummies | yes | yes | yes | yes |
| age dummies | yes | yes | yes | yes |
| industry x year effects | yes | yes | | |
| year effects | | | yes | yes |
| Observations | 102,516 | 102,516 | 102,516 | 102,516 |
| R-squared | 0.186 | 0.186 | 0.010 | -0.023 |
| Number of id | | | 17,736 | 17,736 |

Notes: Robust standard errors (clustered by industry) are in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

# Imported machines use higher quality labor

| Depvar: ln wage | Pooled | | Firm FE | |
|---|---|---|---|---|
| | OLS | IV | OLS | IV |
| having imported (dummy) | 0.151*** | 0.586*** | 0.089*** | 0.796*** |
| | (0.009) | (0.049) | (0.009) | (0.090) |
| foreign (dummy) | 0.280*** | 0.125*** | 0.089** | -0.037 |
| | (0.017) | (0.024) | (0.036) | (0.041) |
| size dummies | yes | yes | yes | yes |
| age dummies | yes | yes | yes | yes |
| industry x year effects | yes | yes | | |
| year effects | | | yes | yes |
| Observations | 102,516 | 102,516 | 102,516 | 102,516 |
| R-squared | 0.463 | 0.417 | 0.587 | 0.523 |
| Number of id | | | 17,736 | 17,736 |

Notes: Robust standard errors (clustered by industry) are in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$