The Impact of Electrification on Quality and Productivity: Evidence from Japanese Cotton Spinning

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Issues

- **Electricity grid expansion in Japan after 1900**

  $\Rightarrow$ *Adoption of New Technology (Electric Engines)*

  $\Rightarrow$ *Impact on Productivity and Product Quality?*

- **Methodological Challenge**: How to estimate production functions with unobserved quality and productivity?

  - Estimating quantity-based production functions directly from quantity data is problematic if products differ in quality.
  - Observed price differences reflect variations in both product quality and markups.

    $\Rightarrow$ Prices cannot directly control for quality differences.

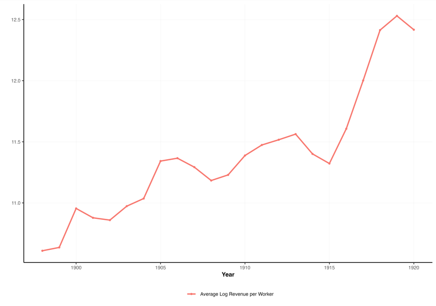
Japan's cotton-spinning industry, 1897–1920

- Data from Braguinsky, Ohyama, Okazaki, and Syverson (2015)
- Single product: Cotton Yarn
- Price and quantity data
- Adoption of New Technology for Machines:

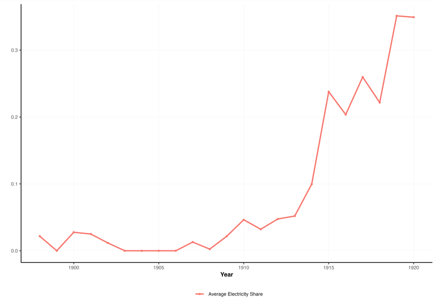
  $$\text{Steam Engine} \Rightarrow \text{Electric Engine}$$

- Electricity Grid Expansion (Kotani, 2025)

Revenue per Worker and Adoption of Electric Engines in the Japanese Cotton Spinning Industry, 1898–1920

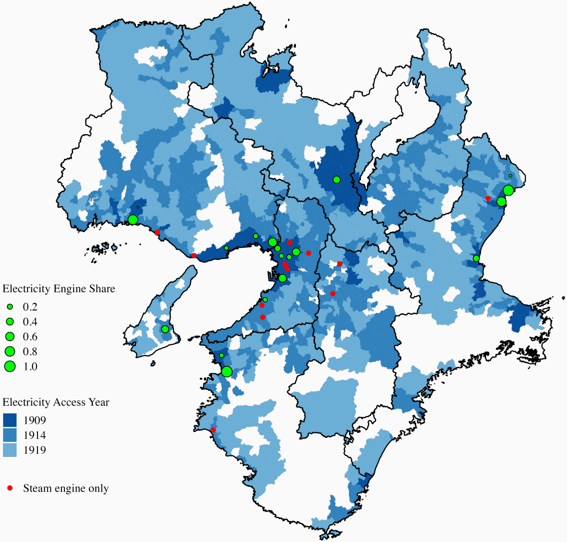


Avg. Revenue per Worker



Electric Engine Shares

Electricity Access and Electric Engine Shares in 1920



Electricity access and Electric Engine Shares in Kansai, Japan, 1920

Adoption of Electrically-powered Ring Spindles

"[In Lancashire], taken as a conservative estimate...the increase in production is on the average at least 5 per-cent. The improvement in value...has been given as any-thing up to 2.5 percent." — Wilson (1909, p. 756)

- **Steam-powered ring spindles**: faced frictional losses, unstable speeds, and limited spindle speeds due to mechanical inefficiencies.
- **Electrically-powered ring spindles**: overcame these constraints, enabling higher spindle speeds, greater energy efficiency, easier maintenance, and improved yarn quality.

Contribution

- A new method for estimating production function with unobserved quality and productivity from quantity and price data
- Non-parametric identification
- Parametric Estimator: CES Demand + Cobb-Douglas Production + VAR (1) Processes for quality and TFPQ (quantity-based productivity)
- Effects of Electrification on quality and productivity in the Japanese cotton spinning

Literature Review

- Ignoring quality differences biases productivity estimates

  Foster, Haltiwanger, and Syverson (2008), Aw, Roberts, and Xu (2011), Grieco, Li, and Zhang (2016)

- Price differences reflect quality and markup

  Melitz and Ottaviano (2008), De Loecker (2011), De Loecker and Warzynski (2012), Kugler and Verhoogen (2012), Atkin, Khandelwal, and Osman (2019)

- Production function estimation

  Olley and Pakes (1996), Levinsohn and Petrin (2001), Ackerberg et al. (2015), De Loecker et. al (2016), Kasahara and Sugita (2023)

- Japanese Cotton Spinning industry

  Braguinsky, Ohyama, Okazaki, and Syverson (2015), Braguinsky, Ohyama, Okazaki, and Syverson (2021)

- Electrification in the US and Japan

  Minami (1977), Devine (1983), David (1990), Okazaki (2001), Fiszbein et al. (2020), Kotani (2025)

Production function estimation with unobserved quality and productivity from quantity and price data

Setup: Demand function under monopolistic competition

- Inverse demand function for **quality-adjusted** output and price:

$$\tilde{P}_{it} = \Psi_t(\tilde{Y}_{it}), \quad \frac{d\Psi_t(\tilde{Y})}{d\tilde{Y}} < 0,$$

where

$$\underbrace{\tilde{P}_{it}}_{\text{quality-adj. price}} := \underbrace{P_{it}}_{\text{price}} / \underbrace{\Delta_{it}}_{\text{quality}},$$

$$\underbrace{\tilde{Y}_{it}}_{\text{quality-adj. output}} := \underbrace{Y_{it}}_{\text{output}} \times \underbrace{\Delta_{it}}_{\text{quality}}$$

- CES demand function:

$$P_{it}/\Delta_{it} = \underbrace{(Y_{it}\Delta_{it})^{-1/\sigma}}_{=\Psi_t(\tilde{Y}_{it})} \quad \Leftrightarrow \quad p_{it} - \delta_{it} = -\frac{1}{\sigma}(y_{it} + \delta_{it})$$

Setup: Demand, Revenue, and Production

- Inverse output demand function:

$$p_{it} = -\frac{1}{\sigma} y_{it} + \left(1 - \frac{1}{\sigma}\right) \underbrace{\delta_{it}}_{\text{quality}}$$

- Revenue:

$$r_{it} = p_{it} + y_{it} = \underbrace{\left(1 - \frac{1}{\sigma}\right)}_{:=\mu} (y_{it} + \delta_{it})$$

- Production function:

$$y_{it} = \beta_m m_{it} + \beta_k k_{it} + \beta_l l_{it} + \underbrace{\omega_{it}}_{\text{TFPQ}}$$

where $k_{it} = \mathbb{K}(\mathbb{I}_{t-1})$ is predetermined capital.

Stochastic Processes for TFPQ and Quality

- TFPQ and Quality Processes:

$$\begin{bmatrix} \omega_{it} \\ \delta_{it} \end{bmatrix} = \begin{bmatrix} \rho_{\omega\omega} & \rho_{\omega\delta} \\ \rho_{\delta\omega} & \rho_{\delta\delta} \end{bmatrix} \begin{bmatrix} \omega_{it-1} \\ \delta_{it-1} \end{bmatrix} + \begin{bmatrix} \lambda_{\omega} \\ \lambda_{\delta} \end{bmatrix} z_{it} + \begin{bmatrix} \eta_{it} \\ \epsilon_{it} \end{bmatrix}$$

  where $(\eta_{it}, \epsilon_{it}) \perp\!\!\!\perp (m_{it-1}, l_{it-1}, k_{it}, z_{it}, \omega_{it-1}, \delta_{it-1})$

- z_{it}: electric engine shares, equipment age bins
-

$$\omega_{it} + \delta_{it} = \tilde{\rho}_1(\omega_{it-1} + \delta_{it-1}) + \tilde{\rho}_2 \delta_{it-1} + \tilde{\lambda}_z z_{it} + \underbrace{\eta_{it} + \epsilon_{it}}_{\xi_{it}}$$

  where $\tilde{\rho}_1 = \rho_{\omega\omega} + \rho_{\delta\omega}, \quad \tilde{\rho}_2 = \rho_{\omega\delta} + \rho_{\delta\delta} - \rho_{\omega\omega} - \rho_{\delta\omega}.$

Standard Production Function Case

- Control function for ω_{it}:

$$\begin{aligned} m_{it} &= \mathbb{M}_t(\omega_{it}, k_{it}, \ell_{it}) \qquad \text{(demand function for } m_{it}\text{)} \\ \Rightarrow \quad \omega_{it} &= \mathbb{M}_t^{-1}(m_{it}, k_{it}, \ell_{it}) \qquad \text{(by monotonicity)} \end{aligned}$$

- Stochastic process for ω_{it}:

$$\begin{aligned} \omega_{it} &= \rho\omega_{it-1} + \eta_{it} \\ \Leftrightarrow \quad \mathbb{M}_t^{-1}(m_{it}, k_{it}, \ell_{it}) &= \rho\mathbb{M}_{t-1}^{-1}(m_{it-1}, k_{it-1}, \ell_{it-1}) + \eta_{it} \end{aligned}$$

- ω_{it} is identified under $\eta_{it} \perp\!\!\!\perp (k_{it}, \ell_{it}, m_{it-1}, k_{it-1}, \ell_{it-1})$

Step 1: Control Function for $\omega_{it} + \delta_{it}$

- "Revenue Production Function":

$$r_{it} = (\mu\beta_m)m_{it} + (\mu\beta_k)k_{it} + (\mu\beta_l)l_{it} + \mu(\omega_{it} + \delta_{it})$$

- Demand function for m_{it} (Levinsohn and Petrin, 2003):

$$\begin{aligned} m_{it} &= \mathbb{M}_t(\omega_{it} + \delta_{it}, k_{it}, \ell_{it}) \\ &= \gamma_{0t} + \gamma_{kt}k_{it} + \gamma_{lt}l_{it} + \gamma_{\omega t}(\omega_{it} + \delta_{it}) \end{aligned}$$

- Control function for $\omega_{it} + \delta_{it}$:

$$\begin{aligned} \omega_{it} + \delta_{it} &= \mathbb{M}_t^{-1}(m_{it}, k_{it}, \ell_{it}) \\ &= \frac{1}{\gamma_{\omega t}}\left[m_{it} - \gamma_{0t} - \gamma_{kt}k_{it} - \gamma_{lt}l_{it}\right] \end{aligned}$$

Step 2: Control Function for δ

- FOC for profit maximization w.r.t. m_{it}:

$$r_{it} = \gamma_{mt} + m_{it}$$

- Control function for δ:

$$\begin{aligned} \delta_{it} &= \mu^{-1} r_{it} - y_{it} \\ &= \tilde{\gamma}_{\delta,0} + \mu^{-1} m_{it} - y_{it} \end{aligned}$$

Step 3: Reduced-form OLS

Substituting

$$\omega_{it} + \delta_{it} = \frac{1}{\gamma_{\omega t}} \left[m_{it} - \gamma_{0t} - \gamma_{kt} k_{it} - \gamma_{lt} l_{it} \right]$$

$$\delta_{it} = \tilde{\gamma}_{\delta,0} + \mu^{-1} m_{it} - y_{it}$$

into

$$\omega_{it} + \delta_{it} = \tilde{\rho}_{\omega+\delta}(\omega_{it-1} + \delta_{it-1}) + \tilde{\rho}_{\delta}\delta_{it-1} + \tilde{\lambda}_z z_{it} + \xi_{it}$$

gives

$$m_{it} = \phi_{0t} + \phi_{1t} k_{it} + \phi_{2t} \ell_{it} + \phi_{3t} m_{it-1} + \phi_{4t} k_{it-1} + \phi_{5t} \ell_{it-1} + \phi_{6t} y_{it-1} + \phi_{7t} z_{it} + \xi_{it}$$

$\Rightarrow$ Reduced form OLS coefficients are identified.

Step 3: Identify $\rho_{\omega\omega} + \rho_{\delta\omega}$ and γ_ω

- Identifying the sum of VAR coefficients on lagged TFPQ:

$$\rho_{\omega\omega} + \rho_{\delta\omega} = -\frac{\phi_{4t}}{\phi_{1t}}$$

- Identifying γ_ω:

$$y_{it} - (\rho_{\omega\omega} + \rho_{\delta\omega})y_{it-1} = \iota_{0t} + \frac{1}{\gamma_{\omega t}}\Upsilon_{it} + \iota_{zt}z_{it} + \tilde{\eta}_{it}$$

where Υ_{it} could be constructed from the idetified reduced form OLS coefficients and observed inputs and output.

Step 5: Recover the Structural Parameters

- With $\gamma_{\omega t}$, compute:

$$\mu_t = \frac{1}{\gamma_{\omega t}(1 - s_{mt})}, \quad \beta_m = \frac{s_{mt}}{\gamma_{\omega t}(1 - s_{mt})}, \quad \beta_k = \frac{\phi_{1t}}{\gamma_{\omega t}}, \quad \beta_l = \frac{\phi_{2t}}{\gamma_{\omega t}}$$

where

$$s_{mt} = \frac{\exp(p_{Mt} + m_{it})}{\exp(r_{it})}.$$

- ω_{it} and δ_{it} are identified up to mean-zero normalisation
- VAR system coefficients are identified

Non-parametric Identification

We also analyze non-parametric identification when

$$p_{it} = \psi(y_{it} + \delta_{it}) + \delta_{it},$$
$$y_{it} = f(m_{it}, k_{it}, \ell_{it}) + \omega_{it}$$

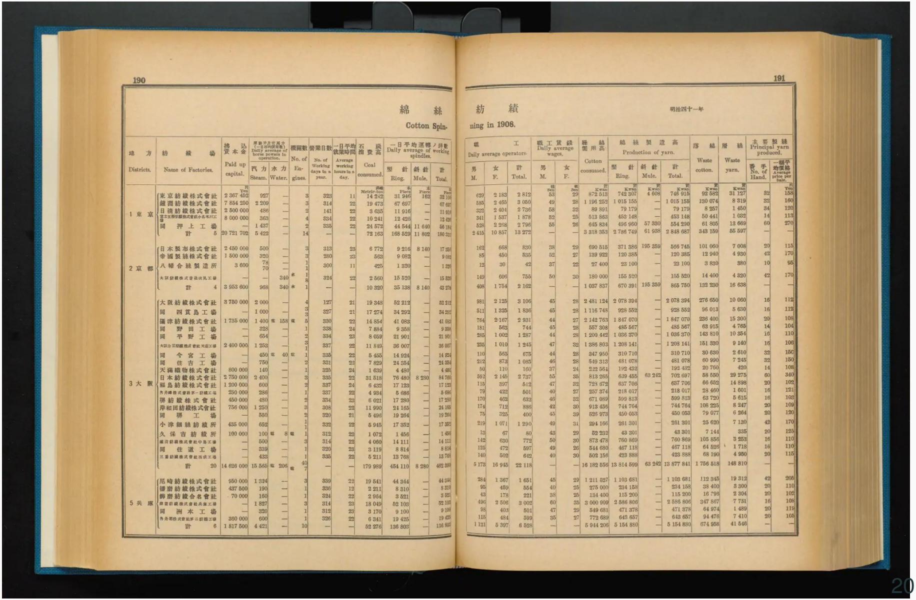
without making any parametric assumption on $\psi(\cdot)$ and $f(\cdot)$.

The Impact of Electrification on quality and productivity in the Japanese cotton spinning

Japanese cotton-spinning industry, 1897–1920

- Unbalanced panel plant-level data from Braguinsky, Ohyama, Okazaki, and Syverson (2015)
- Single product: cotton yarn
- Price, output, capital, labor, and materials
- Adoption of new technology: steam engine vs. electric engine
- Equipment age
- Quality measure: “Count"

Data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Cotton Spinning in 1908.

明治四十一年

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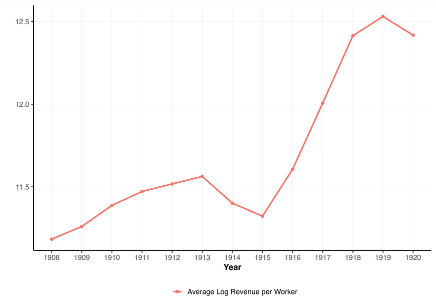
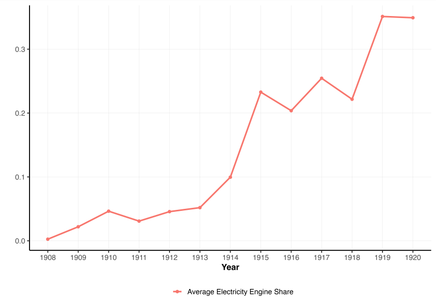
Revenue per Worker and Adoption of Electric Engines in the Japanese Cotton Spinning Industry, 1908–1920

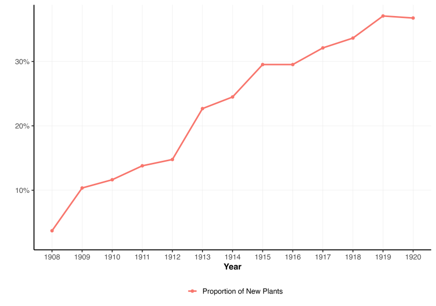


Avg. Revenue per Worker

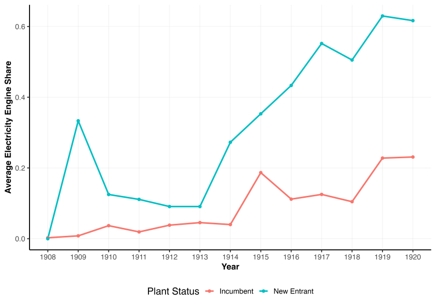


Electric Engine Shares

Plant Entry Rates and Electric Engine Shares



Plant Entry Rates

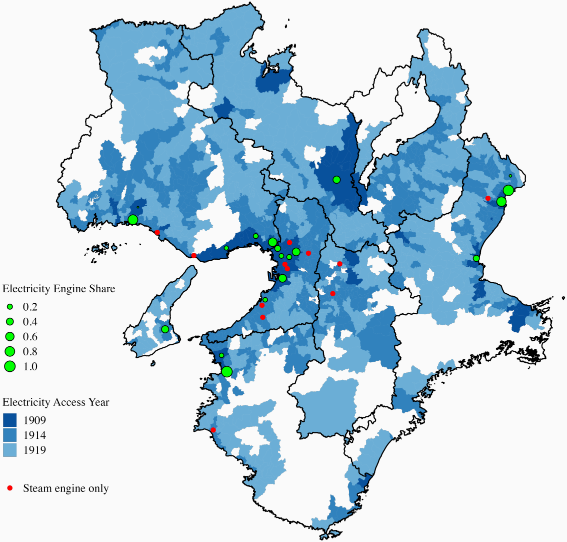


Electric Engine: New vs. Old

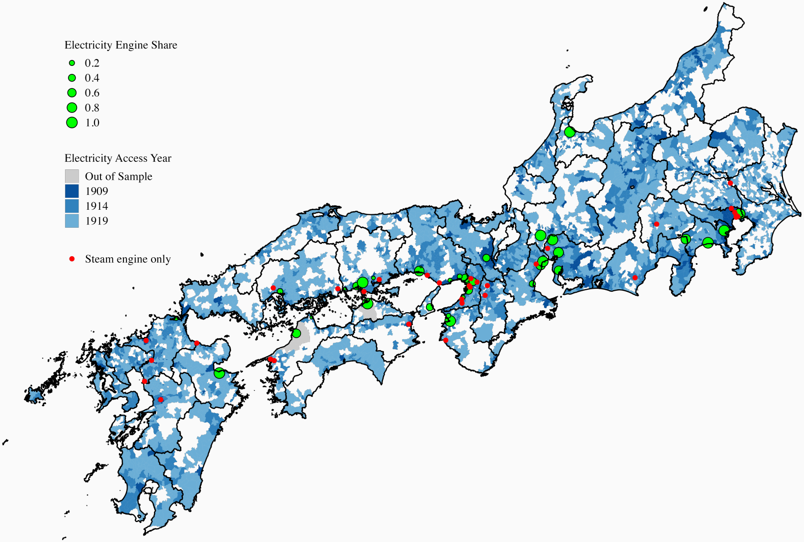
Electricity Grid Expansion

- Covers Japan's industrial development phase, a critical period for electrification
- Municipality-level electricity grid access data from Kotani (2025)
- Tracking electricity grid expansion in 1909, 1914, and 1919

Maps


Electricity Engine Share
0.2
0.4
0.6
0.8
1.0
Electricity Access Year
1909
1914
1919
Steam engine only

Maps


Electricity Engine Share
0.2
0.4
0.6
0.8
1.0
Electricity Access Year
Out of Sample
1909
1914
1919
Steam engine only

Estimation

- Lagged Observables on TFPQ and Quality Processes:
  - Electric Engine share
  - Equipment age in bins
- Electricity Grid expansion as IV for lagged electric engine share

IV Estimation

First-Stage Regression Coefficients (1914–1920)

	Electricity engine share 1914–1920
1909 Electricity Access	0.107***
	(0.033)
Lagged TFPQ	-0.192
	(0.233)
Lagged Quality	0.118***
	(0.042)
Middle-Aged Equipment	-0.363***
	(0.038)
Oldest Equipment	-0.366***
	(0.038)
Time Trend	-0.018
	(0.019)
F-statistic for 1909 Elec. Access	10.51

Table 1: First-stage regression coefficients for lagged electric engine share with standard errors in parentheses. F-statistic on 1909 Electricity Access: 10.51. Two-tailed tests: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Youngest equipment is the reference.

Results - Markup and Output Elasticities (IV)

	1914–1920 (IV)	1914–1920 (OLS)
Markup (μ_{CES})	1.268	1.326
	(0.366)	(0.326)
Materials Elasticity (β_m)	0.901	0.943
	(0.259)	(0.231)
Capital Elasticity (β_k)	0.060	0.037
	(0.095)	(0.078)
Labor Elasticity (β_l)	0.068	0.055
	(0.035)	(0.026)
Sum of Elasticities ($\beta_m + \beta_k + \beta_l$)	1.029	1.035
	(0.244)	(0.213)

Table 2: CES markup and output elasticities with standard errors in parentheses.

- Near-constant returns to scale

Results - TFPQ Process Coefficients (VAR(1), IV)

	1914–1920 (IV)	1914–1920 (OLS)
	ω_{it}	ω_{it}
ω_{it-1}	0.492***	0.484***
	(0.135)	(0.128)
δ_{it-1}	0.001	-0.011
	(0.020)	(0.015)

Table 3: TFPQ process coefficients with standard errors in parentheses. Two-tailed tests: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

- Strong TFPQ persistence
- Insignificant quality-to-TFPQ spillover

Results - TFPQ Process Coefficients (Observables, IV)

	1914–1920 (IV)	1914–1920 (OLS)
	ω_{it}	ω_{it}
Electric Engine Share	-0.227	-0.010
	(0.152)	(0.023)
Middle-Aged Equipment	-0.058	0.017
	(0.060)	(0.020)
Oldest Equipment	-0.082	-0.006
	(0.058)	(0.021)
Time Trend	0.011	0.010
	(0.008)	(0.007)

Table 4: TFPQ process coefficients with standard errors in parentheses. Two-tailed tests: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Youngest equipment is the reference.

- No significant effects of observables on TFPQ

Results - Quality Process Coefficients (VAR(1), IV)

	1914–1920 (IV)	1914–1920 (OLS)
	δ_{it}	δ_{it}
δ_{it-1}	0.142**	0.271***
	(0.064)	(0.037)
ω_{it-1}	-0.885**	-1.156***
	(0.426)	(0.324)

Table 5: Quality process coefficients with standard errors in parentheses. Two-tailed tests: *** p < 0.01, ** p < 0.05, * p < 0.10.

- Significant quality persistence
- Negative estimate for $\rho_{\delta\omega}$: To improve quality, lower TFPQ is required.

Results - Quality Process Coefficients (Observables, IV)

	1914–1920 (IV) δ_{it}	1914–1920 (OLS) δ_{it}
Electric Engine Share	1.402***	0.104*
	(0.481)	(0.058)
Middle-Aged Equipment	0.479**	0.014
	(0.189)	(0.051)
Oldest Equipment	0.428**	0.018
	(0.184)	(0.052)
Time Trend	0.246***	0.246***
	(0.024)	(0.017)

Table 6: Quality process coefficients with standard errors in parentheses. Two-tailed tests: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Youngest equipment is the reference.

- Significant positive effects of electric engine share
- Significant “learning-by-doing” effect on equipment age

Results - Correlations (IV)

Correlation btw ...	1914–1920 (IV)
Electric Engine Share & TFPQ (ω_{it})	-0.034
	(0.073)
Electric Engine Share & Quality (δ_{it})	0.239***
	(0.076)
Quality (δ_{it}) & TFPQ (ω_{it})	-0.073
	(0.205)
Quality (δ_{it})& "Count"	0.235***
(Validation)	(0.069)

Table 7: Correlation coefficients with standard errors in parentheses. Two-tailed tests: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Regression of Quality on Yarn Count Bins (1914–1920)

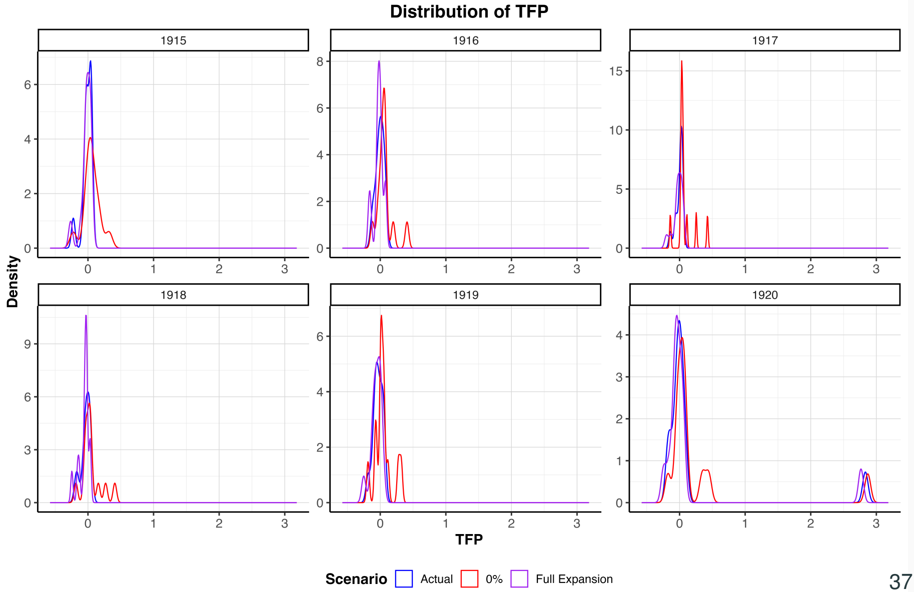
	1914–1920
	δ_{it}
(Intercept)	-0.078
	(0.051)
Count 18–30	-0.017
	(0.068)
Count 31–50	0.290***
	(0.086)
Count 51+	0.881***
	(0.165)

Table 8: Regression coefficients for quality measure on yarn count bins with standard errors in parentheses. Two-tailed tests: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Counts <18 is the reference group.

Counterfactual Analysis: Impact of Electric Engine Adoption on Quality, TFPQ, Price, and Output

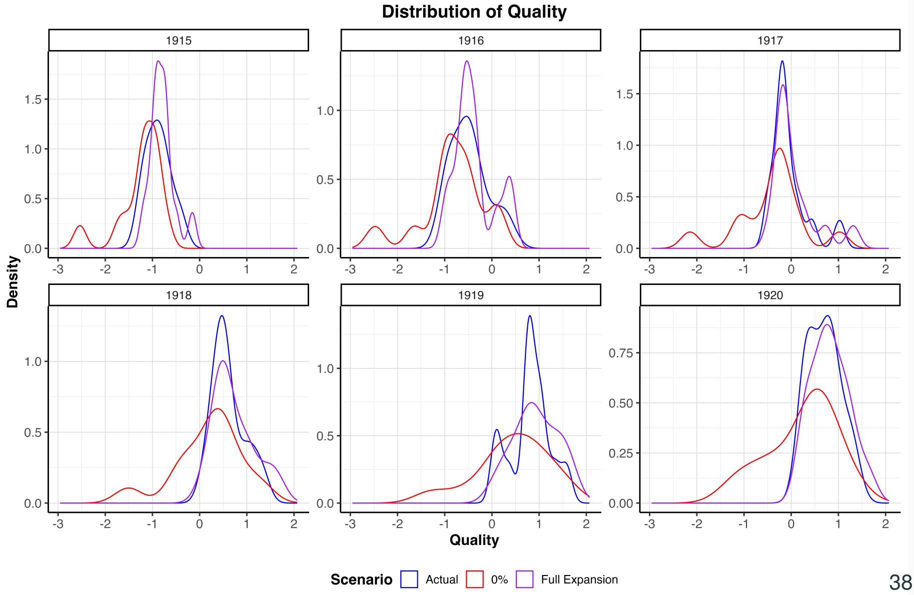
- Evaluate three scenarios:
  1. Actual Electric Engine Share
  2. No Adoption
  3. Full Electricity Grid Expansion
- For each plant:
  1. Start from the estimated TFPQ and quality in 1914 ($\hat{\omega}_{i,1914}, \hat{\delta}_{i,1914}$)
  2. TFPQ (ω_{it}) and quality (δ_{it}) evolve via a VAR(1) model under counterfactual electric engine shares
  3. $\hat{\eta}_{it}$ and $\hat{\epsilon}_{it}$ are invariant under counterfactual

TFP



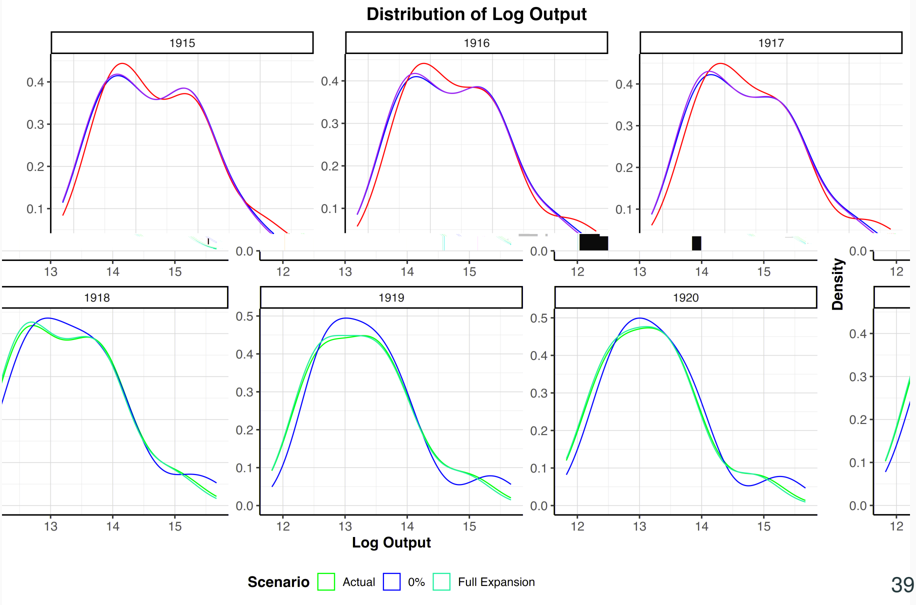
Distribution of TFP
1915
1916
1917
1918
1919
1920
Density
TFP
Scenario
Actual
0%
Full Expansion

Quality

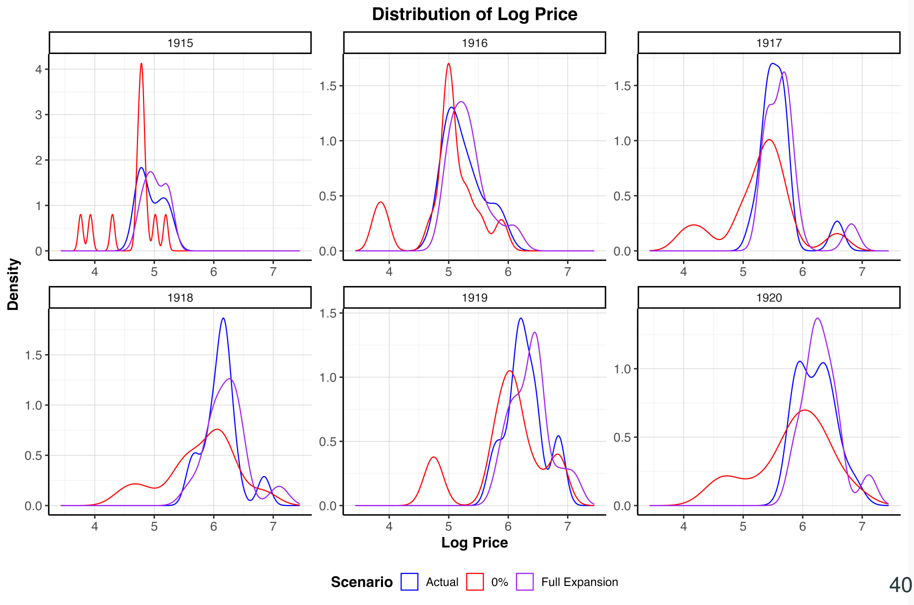


Distribution of Quality
1915
1916
1917
1918
1919
1920
Density
Quality
Scenario
Actual
0%
Full Expansion

Log Output


Distribution of Log Output
1915
1916
1917
1918
1919
1920
Density
Log Output
Scenario
Actual
0%
Full Expansion

Log Price



Distribution of Log Price
1915
1916
1917
1918
1919
1920
Density
Log Price
4
5
6
7
0
1
2
3
0.0
0.5
1.0
1.5
Scenario
Actual
0%
Full Expansion

Counterfactual Average Across Scenarios: 1915–1920

	Actual	0%	Full Grid Expans.
Lagged Electric Engine Share	0.203	0.000	0.259
Quality	0.117	-0.272	0.227
TFPQ	0.018	0.097	-0.004
Log Output	13.301	13.380	13.279
Log Price	5.735	5.410	5.827
Log Revenue	19.035	18.790	19.104

Table 9: Average model-implied outcomes (Quality, TFPQ, Log Output, Log Price, Log Revenue, Lagged Electric Engine Share) for 1915–1920, comparing actual data (Actual), no electricity adoption (0%), and full electricity grid access in 1909 (Full Grid Expans.).

Conclusion

- **Electrification significantly improved product quality** in the Japanese cotton spinning industry.
- Quality improvements often accompanied by slight reductions in quantity-based productivity.
- **New estimation method effectively handles unobserved quality and productivity**