Population Aging, Skill-Composition, and Technology Adoption

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Introduction

- The workforce is aging in most developed economies.
  - Share 45+ in US: $\uparrow$ from 38.5% in 2004 to 42%, and to 44.5% by 2034. [BLS]
- Aging affects the skill-mix of the workforce
  - Older workers bring more experience accumulated on the job. [Ben-Porath, 1967]
  - Younger workers bring more up-to-date skills [Deming and Noray, 2020]

Introduction

- The workforce is aging in most developed economies.
  - Share 45+ in US: $\uparrow$ from 38.5% in 2004 to 42%, and to 44.5% by 2034. [BLS]

- Aging affects the skill-mix of the workforce ...

- ... And generates a trade-off for aggregate productivity
  - Old workers $\uparrow \implies$ experience $\uparrow \implies$ Productivity $\uparrow$.
  - Young workers $\downarrow \implies$ tech-skills $\downarrow \implies$ Technology Adoption $\downarrow \implies$ Productivity $\downarrow$

- Net effect is ex-ante ambiguous and depend on multiple factors
  - e.g., complementarity b/w skills, speed of tech progress, cost of retraining.

Q. What is the impact of population aging on aggregate labor productivity?

Related Literature

- Effect of population aging on firm dynamics and TFP.

  Maestas et al. [2023], Aksoy et al. [2019], Hopenhayn et al. [2022], Bloom et al. [2020], Karahan et al. [2024], Angelini [2023], Inokuma and Sanchez [2023], Peters and Walsh [2021]

  - Our Paper: Aging change the workforce composition, not only the size of labor force.

- Vintage human capital and technology diffusion.

  Chari and Hopenhayn [1991],MacDonald and Weisbach [2004],Adão et al. [2024], Violante [2002]

  - Our Paper: Multi-dimensional skills that are portable across technologies.

- Workers Age and New Technologies

  Lipowski [2024],Deng et al. [2024],Deming and Noray [2020], Acemoglu and Restrepo [2022]

  - Our Paper: Young workers are an important input for technology adoption of firms.

Today's Talk

Empirics: Show that young workers have a comparative advantage in new technologies.

- Firms with Younger workforce: Prob. Adopt Tech $\uparrow$.
- Young workers: Prob. tech-related tasks $\uparrow$ + Productivity Gains from Adoption.
- Adoption tilts workforce toward young workers.

Theory: Model with firm dynamics + labor market frictions + multi-dimensional skills.

- Experience + Tech-Skills: evolve over workers career.
- Firms choose between frontier and laggard technology.
- Frontier technology is tech-skill intensive.

Q. Decompose the impact of population aging on aggregate labor productivity.

- Technology Adoption + Matching Frictions under skill-scarcity.

Outline

1. Empirical Analysis
2. The Model
3. Productivity and Misallocation

Data

Main Goal: Link firm-level tech adoption to info on workforce composition.

German Admin Data: Matched Employer Employee + Tech Adoption Surveys.

- Linked Employer-Employee (1993-2021)
  - Firms: Workforce Composition, Investment, On-the-job training.
  - Workers: Wage, Occupations, Unempl. Spells, Education, Demographics.
- LPP (2015, 2019, 2021): Survey of ICT adoption
  - Digital: e.g., IoT, Big Data Analytics, AI, Virtual Reality.
  - Automation: e.g., Robots, Drones, Additive Manufacturing.

Tech Adoption: At least one technology adopted in the last two years. LPP Details

Workforce Composition and Tech Adoption

Q. Are firms with a younger workforce more likely to adopt advanced tech?

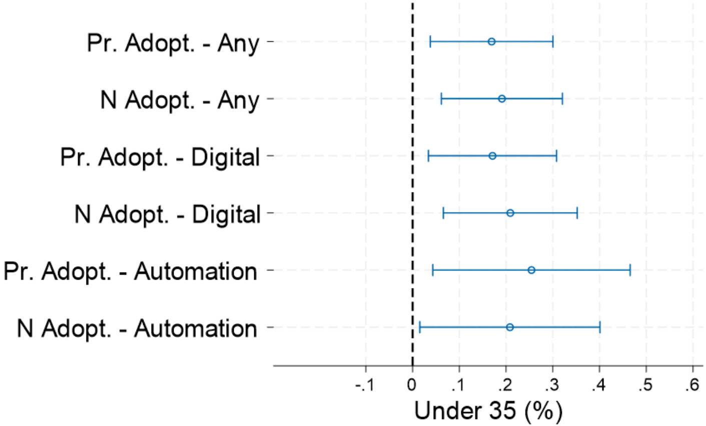
Empirical Specification

$$\mathbb{I}(\text{Adopt})_t = \alpha + \beta \text{ Under 35 } (\%)_{t-1} + \Gamma X_{t-1} + \varepsilon_t$$

- Baseline Controls (X_{t-1}): Firm Size, Firm age, Avg. Wage, College (%), Hiring Rate, Type of Owner.
- Fixed Effects: Sector 3-digit, State, Year, # Tech already used.

Young Workforce Predicts Higher Adoption

- Moving Up by 1-SD of distribution of U35 % $\implies$ Pr. Adopt $\uparrow$ by 20%.
  $\implies$ # Adoption $\uparrow$ by 20%.



Under 40 Full controls

Tasks and Tech Effect on Workers

Q1. Are younger workers more likely to carry out tech-related tasks?

Q2. How do new technologies affect workers' tasks and productivity?

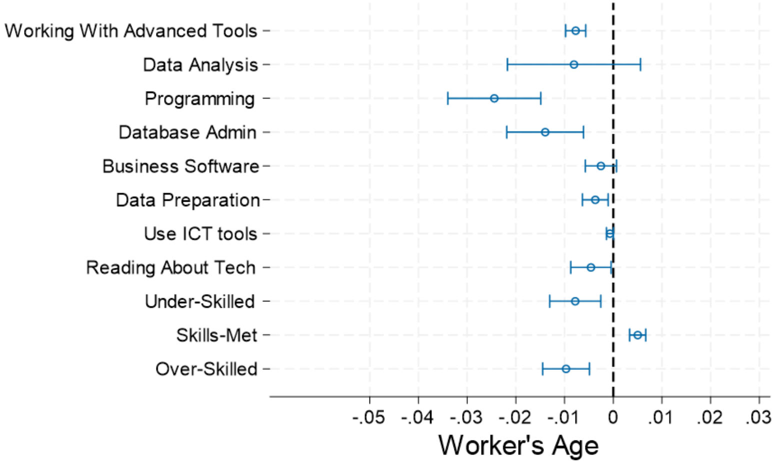
Empirical Specification

$$\mathbb{I}(\mathrm{Y}_{it}) = \alpha + \beta\ \mathrm{Age}_{it} + \Gamma X_{it} + \underbrace{\gamma_{f(it)}}_{\text{Firm FE}} + \varepsilon_{it}$$

- Outcomes (Y_{it})
  - Task-Related Questions
  - Impact of Tech
- Baseline Controls (X_{it}): Wage, Occupation Tenure, Firm Age.
- Fixed Effects: Firm, Year, Task Complexity, College, Occupation (3-digit)

Young Perform More Tech-Related Tasks

- Coefficient: 1 year more $\iff$ Pr. Answer Yes.



Full Controls

Young Report Productivity Gains for Tech Adoption

- Coefficient: 1 year more $\iff$ Pr. Answer Yes.

Full Controls

Event Study Around Adoption

Q. How does firms' employment and workforce composition change after adoption?

Empirical Strategy

- Compare dynamic outcomes of adopting vs non-adopting establishments.

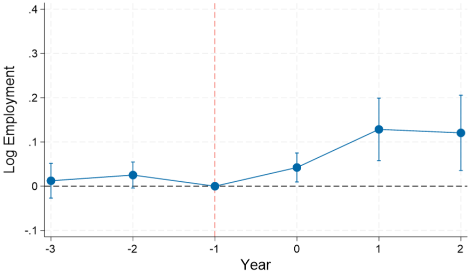
Empirical Specification

$$y_{ft} = \alpha_f + \gamma_t + \sum_k \underbrace{\theta_k D_{ft}^k}_{\text{Non-Adopters}} + \sum_k \underbrace{\beta_k (D_{ft}^k \times \text{Tech Adoption}_f)}_{\text{Adopters}} + \varepsilon_{ft},$$

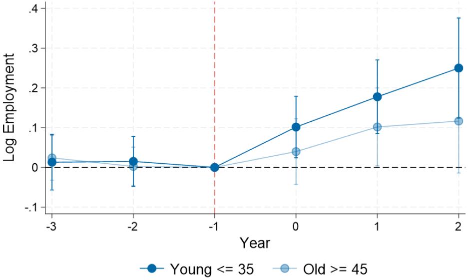
- Outcomes (y_{ft}): Log-Employment, Empl. Composition, Empl. Shares, Wages
- Fixed Effects: Establishment, Sector 3-digit, State, Year.

Event Study - Employment

- Firms expand employment primarily by hiring young.



(a) Log Employment

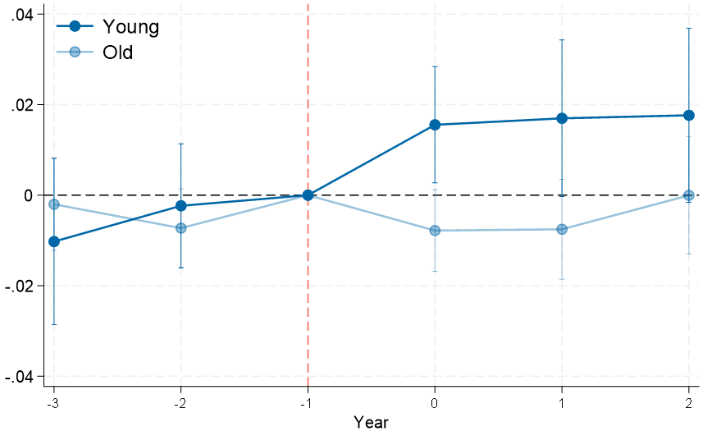


(b) Age Heterogeneity

Empl. Share | Under 40 | College | Automation Tech

Event Study - Incumbent Workers

- Young Incumbents enjoy higher earnings $\implies$ Productivity Gains.



Outline

1. Empirical Analysis

2. The Model

3. Productivity and Misallocation

Overview of the Model

- Model Ingredients
  1. Firm Dynamics + Endogenous Technology Adoption.
  2. Workers are heterogeneous in Tech-Skills and Experience.
  3. Workforce is a state variable for the firms → Frictional Labor Market.
     - Directed Search from Unemployment.
- Purpose of the Model
  1. Decompose impact of population aging on productivity into multiple-channels
     - Technology Adoption.
     - Firm Dynamics + Allocation of workers to firms via search frictions.
  2. Policy Counterfactuals: e.g., subsidy to on-the-job training / changing firing costs.

Agents

Multi-worker firms

State variables: $(\vec{n},\ \tau,\ z)$

- Workforce Composition
- Technological Level: Endogenous
- Idiosyncratic Productivity: Exogenous

Choose:

- Technology investment (a)
- Hiring market and effort (v, W)
- Employees' long-term contract $(\mathcal{C})$

Workers

State variables:

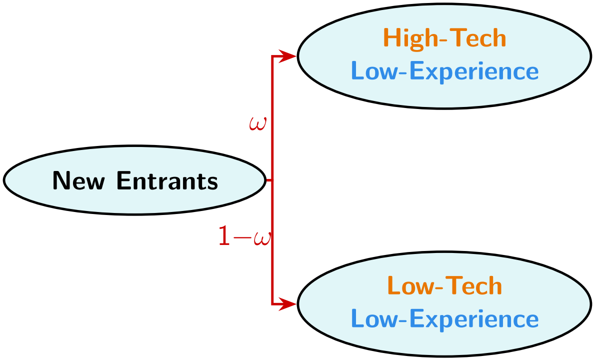
- Tech skills, H/L: $s_T \in \{\gamma_T^H, \gamma_T^L\}$
- Experience, H/L: $s_E \in \{\gamma_E^H, \gamma_E^L\}$

$\Longrightarrow$ Four types: $s \in \mathcal{S} \equiv \{LL, LH, HL, HH\}$

Choose:

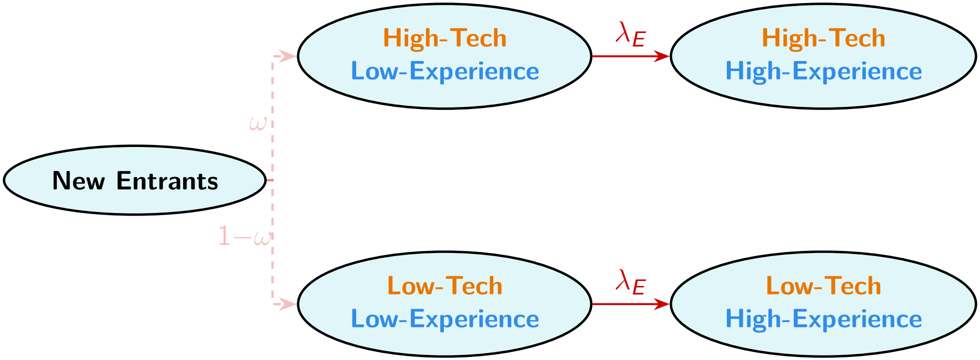
- Hiring market, when unemployed

Workers: Skill Transitions



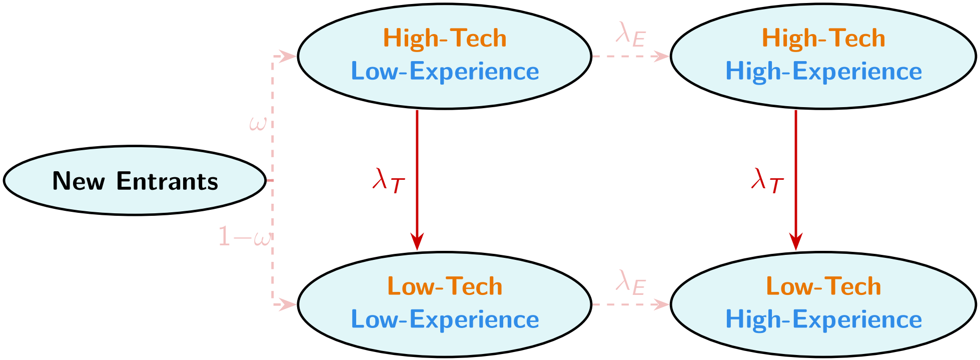
- A share ω of new workers start with **High-Tech**, all have **Low-Experience**

Workers: Skill Transitions



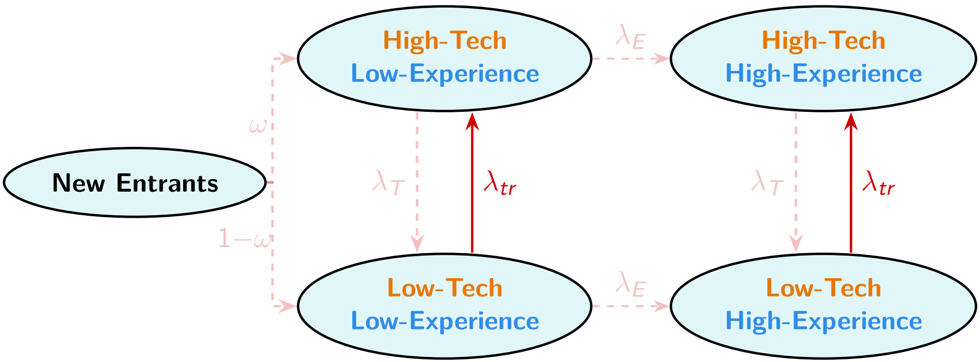
- Workers accumulate experience at rate λ_E.

Workers: Skill Transitions



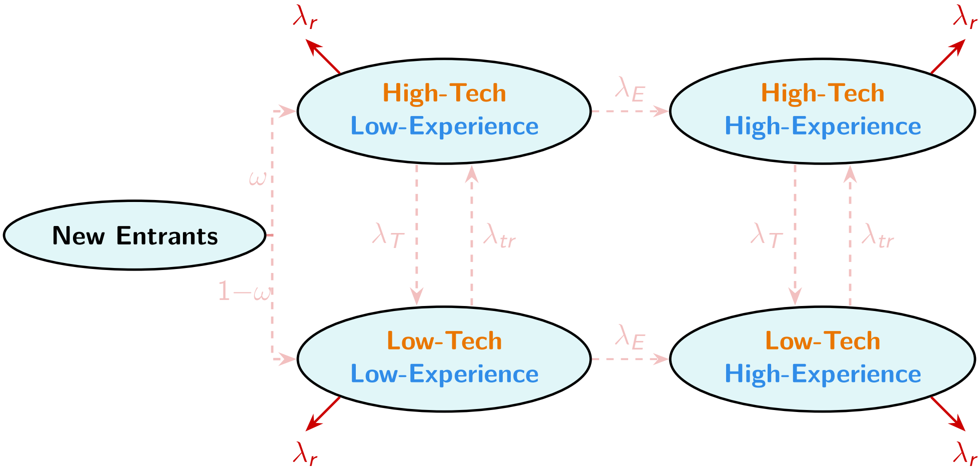
- Tech skills become obsolete at rate λ_T.

Workers: Skill Transitions



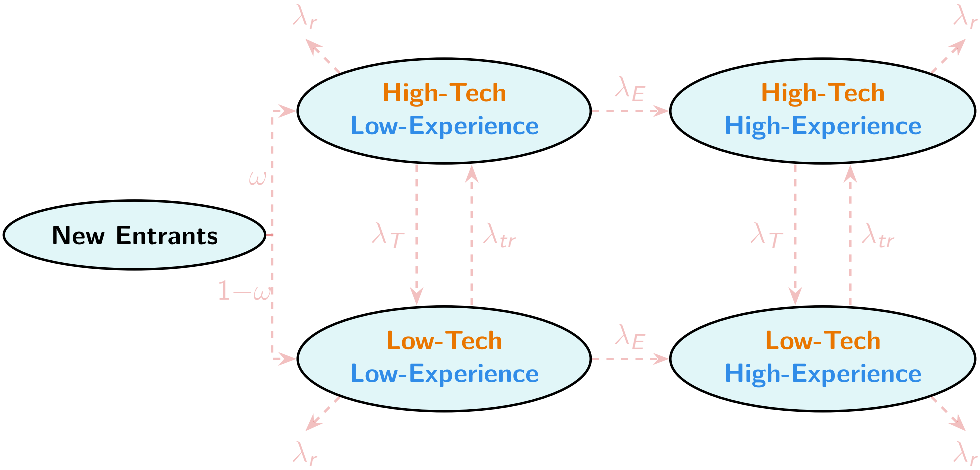
- Firms can retrain workers at rate λ_{tr}.

Workers: Skill Transitions



- Workers retire at rate λ_r.

Workers: Skill Transitions



- Population $\mathcal{L}$ evolves according to $\underbrace{\mu_t}_{\text{New Entrants}} = \mathcal{L}_t \underbrace{\mathbf{g}}_{\text{Population growth rate}} + \underbrace{\lambda_r \mathcal{L}_t}_{\text{Retirement}}$

Timeline

Beginning of period t → **Production** → **Endogenous Decisions** → **Transitions** → *New period $t+1$*

Beginning of period t

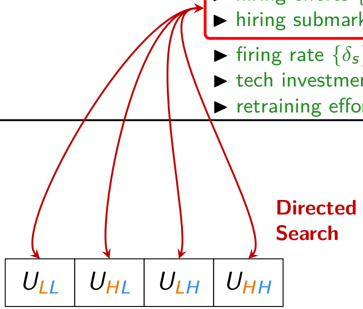
Firms described by:
- Workforce $\vec{n} = \{n_s\}_s$
- Productivity z
- Technology τ

Production

- firms produce $y(z, \tau, \vec{n})$
- wages are paid

Endogenous Decisions

Firms choose:
- hiring efforts $\{v_s\}_s$
- hiring submarkets $\{W_s\}_s$
- firing rate $\{\delta_s\}_s$
- tech investment a
- retraining effort $C(\lambda_{tr})$



Transitions

One transition is realized:
- hiring $\{v_s \eta_s(W_s)\}_s$
- firms dissolution s_F,
- worker separation $\{s_s^W, \delta_s\}_s, \lambda_r$
- tech change $\mathbb{P}(a)$
- skill change $\lambda_{tr}, \lambda_T, \lambda_P$
- productivity shock $F_z(z'|z)$

Production Technologies

- At any instant, two technologies are available:
  - Frontier ($\tau = 0$) and Laggard ($\tau = 1$)

- The production function of technology τ is

$$y_\tau = \underbrace{z\lambda^{-\tau}}_{\text{TFP}} \underbrace{\left[\alpha_\tau L_T^\varphi + (1-\alpha_\tau) L_E^\varphi\right]^{\frac{\eta}{\varphi}}}_{\text{Labor Composite}}, \quad \eta < 1$$

- **A1.** $\lambda > 1 \implies$ Frontier (τ=0) have higher TFP.
- **A2.** $\alpha_0 > \alpha_1 \implies$ Frontier (τ=0) are more tech-skill intensive.

Production Technologies

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- **Task Assignment.** Given a firm's workforce $\vec{n} = \{n_s\}_{s\in\mathcal{S}}$

$$L_T = \gamma_T^H \underbrace{\left(n_{HH}^T + n_{HL}^T\right)}_{\text{High}} + \gamma_T^L \underbrace{\left(n_{LL}^T + n_{LH}^T\right)}_{\text{Low}} \qquad \text{(Tech-Skill)}$$

$$L_E = \gamma_E^H \underbrace{\left(n_{HH}^E + n_{LH}^E\right)}_{\text{High}} + \gamma_E^L \underbrace{\left(n_{LL}^E + n_{HL}^E\right)}_{\text{Low}} \qquad \text{(Experience)}$$

Production Technologies

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- **Technology Transitions.** Firms can invest $a \geq \mathbf{0}$ to affect the following
  - **Tech-Upgrade**. Laggard become Frontier at rate $q_{10}(\underset{+}{\mathbf{a}})$
  - **Tech-Downgrade**. Frontier become Laggard at rate $q_{01}(\underset{-}{\mathbf{a}})$
  - **Obsolescence**. Laggard firms exit the market at rate $q_{12}(\underset{-}{\mathbf{a}})$

Tech Transitions Cyclical Upgrade

Firm Problem

- State Variables: $\vec{s} \equiv (z, \tau, \vec{n}, \vec{W}) = (z, \tau, \{n_i, W_i\}_{i \in \mathcal{S}}), \quad \vec{n} \in \mathcal{N}_+^4$
- Hiring Process: firms post one vacancy for each skill type $i \in \mathcal{S}$
- **Dynamic contracts**

$$\mathcal{C}(s) = \left\{ \{w_i,\ v_i,\ \delta_i,\ W_i'(s_i^+)\}_{i \in \mathcal{S}},\ \ \lambda_{tr},\ \ a_\tau \right\}$$

subject to promise keeping constraint + worker's participation constraint.

- **Exogenous Shocks**
  - Productivity Shocks: $F(z'|z)$
  - Firm Dissolution: s^F
  - Worker Separation: $s_i^W, \ \forall i \in \mathcal{S}$
  - Skill obsolescence / experience: λ_T, λ_E
  - Retirement: λ_r

Transitions Notation Firm's Value Function

Key Property of the Problem

- Define the Joint Surplus: $\Sigma(\vec{n}, z, \tau) \equiv \underbrace{J(\vec{s})}_{\text{Firm's Value}} + \sum_i n_i \underbrace{W_i}_{\text{Worker's Value}}$

Proposition (Schaal [2017])

Solving the firm's problem is equivalent to maximize to joint surplus:

$$\mathcal{C}^{\Sigma} = \Big\{ \{ \underbrace{v_i}_{\text{Recruitment}}, \underbrace{\delta_i}_{\text{Firing}}, \underbrace{W_i'(s_i^+)}_{\text{Continuation Promise}} \}_{i \in \mathcal{S}}, \underbrace{\lambda_{tr}}_{\text{Re-training}}, \underbrace{a_\tau}_{\text{Tech Investment}} \Big\}$$

Key Result

- The joint surplus doesn't depend on promised utilities $\rightarrow$ $s = (\vec{n}, z, \tau)$

Assumptions Value Function

Workers' Continuation Promises

- Assume Cobb-Douglas matching function with matching elasticity γ,

$$M(V,U) = V^{\gamma} U^{1-\gamma}.$$

- The worker's continuation promise is

$$W_i'(s_i^+) \;=\; \gamma \mathcal{U}_i \;+\; (1-\gamma) \underbrace{\left[\Sigma(s_i^+) - \Sigma(s)\right]}_{\text{Surplus Gain from Hiring}}, \quad \forall i \in \mathcal{S},$$

  equivalent to Nash bargaining solution evaluated at the Hosios condition.

- Wages are pinned down by promise keeping constraint holding with equality.

BGP

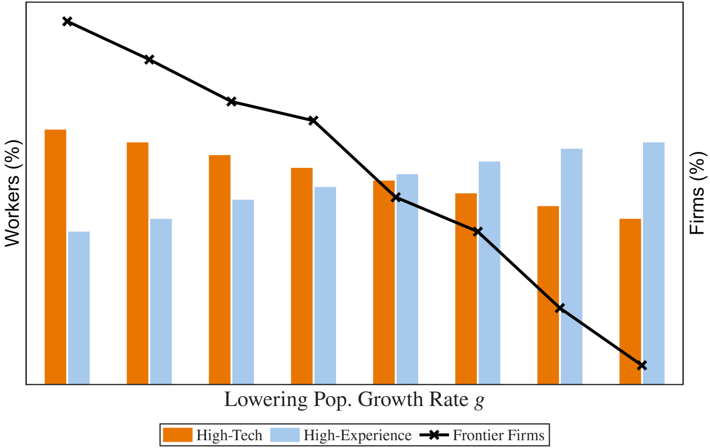
A stationary equilibrium consists of value functions $J(s), W(s), \Sigma(s)$, $\left\{w_i(s), v_i(s), \delta_i(s), W_i'(s)\right\}_{i\in\mathcal{S}}, \pi_e(s), a_\tau(s)$, unemployment values $\{\mathcal{U}_i\}_{i\in\mathcal{S}}$, a per-capita distribution $\Lambda(s)$, per-capita masses of active firms F and entrants F_e, per capita measures of employment and unemployment per each type $\{E_i, U_i\}_{i\in\mathcal{S}}$, such that:

- ***Optimality holds***.
- ***Distributions and measures per capita are stationary***.
- ***Free-entry holds***: $J^e = 0$

Free Entry Calibration Strategy

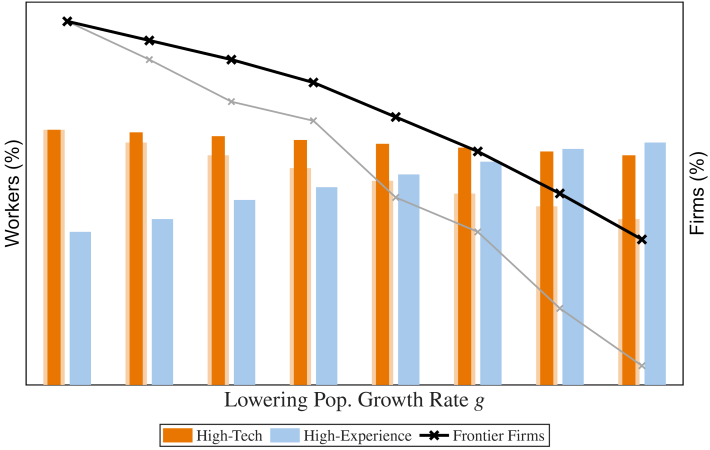
Aging, Skill Composition and Technology Adoption

- **Lowering g** $\implies$ Experience $\uparrow$, Tech-Skills $\downarrow$, Frontier Adoption $\downarrow$.



Aging, Skill Composition and Technology Adoption

- **Low Training Cost** $\Longrightarrow$ Smoother Transition of Skills and Adoption.



Outline

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Aggregate Productivity

Aggregate Productivity: output per-worker ($\mathcal{Y}/E$).

Productivity Decomposition

$$\text{Productivity} = \underbrace{(\text{Avg Size})^{1-\eta}}_{\text{DRS}} \times \text{Avg (Standardized) Output} =$$

$$= (\text{Avg Size})^{1-\eta} \times \underbrace{\sum_{z,\tau} \text{Share}(z,\tau)}_{\text{Productivity Selection}} \times \text{Avg (Standardized) Output}(z,\tau)$$

$$= (\text{Avg Size})^{1-\eta} \times \sum_{z,\tau} \text{Share}(z,\tau) \times \sum_{\substack{\text{Scale} \\ n}} \sum_{\substack{\text{Composition} \\ m}} \text{Output}(n,m) \times \underbrace{\text{Share}(m|n)}_{\substack{\text{Within-firm} \\ \text{Misallocation}}} \times \underbrace{\text{Share}(n)}_{\substack{\text{Between-firm} \\ \text{Misallocation}}}$$

Derivation

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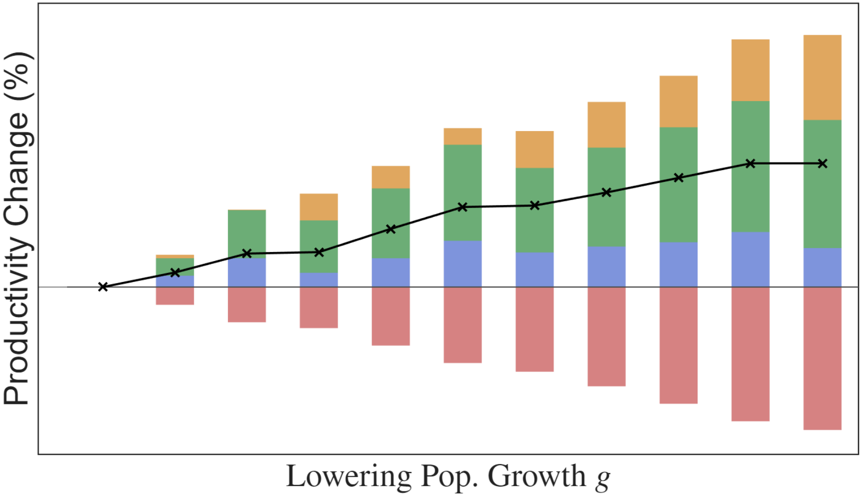
Derivation

Productivity Decomposition

- Low g $\Longrightarrow$ $\uparrow$ Loss from Productivity Selection.

Simulation



Conclusions and Next Steps

- Aging reshuffles the economy's skill mix: experience $\uparrow$, tech-skills $\downarrow$.
- Impact on aggregate productivity depends on the effect on tech adoption and labor misallocation.
- Construct a model that can separate various effects and suggest targeted policy interventions.
- **Next Steps**:
  - Calibrate the model using German data.
  - Feed projected future population aging path and study the effect on productivity.
  - Perform policy analysis: training cost $\downarrow$, firing costs $\downarrow$.

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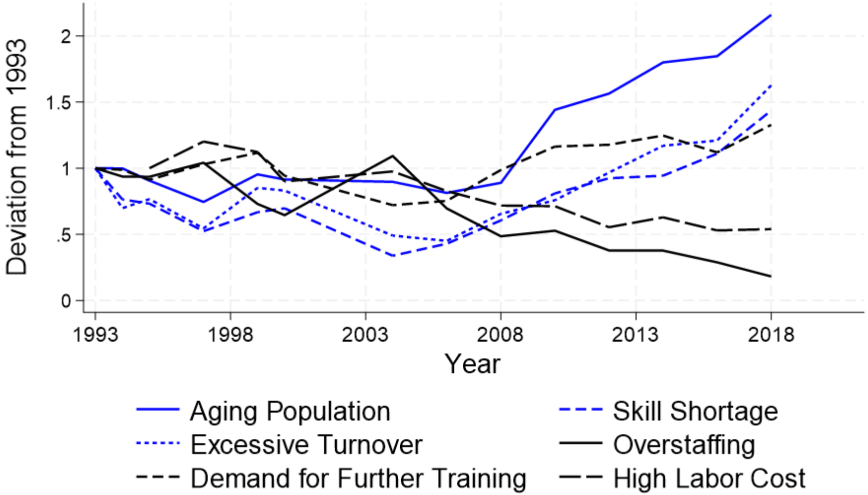
Main Concerns About Staffing



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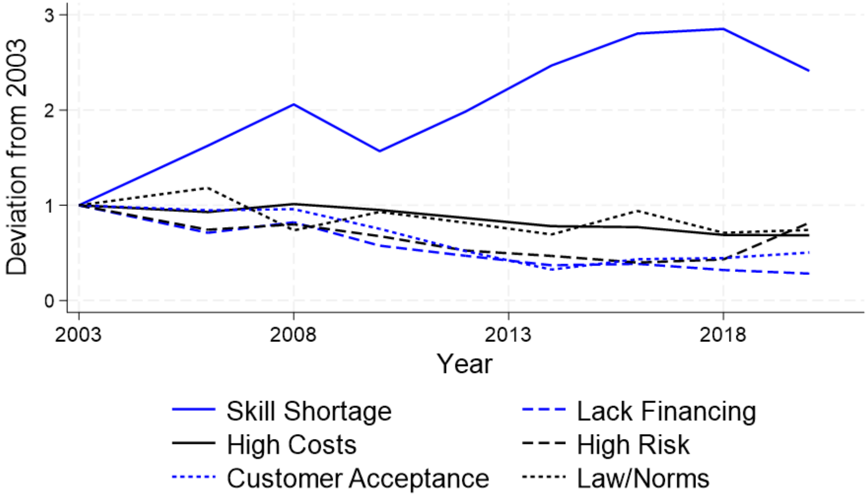
Main Constraints to Innovation



LPP-ADIAB Overview

- Sample: $\approx$ 750 establishments per wave.
  - Representative of firms $>$ 50 employees.
  - Representative survey of employees are surveyed (7 per firm avg.)
- Advanced technologies surveyed
  - Digital: e.g., IoT, Big Data Analytics, AI, Virtual Reality.
  - Automation: e.g., Robots, Drones, Additive Manufacturing.
- Usage Options (for each tech.)
  - Use $<$ 2 years ago $\rightarrow$ Adoption Event at $t-2$.
  - Use $>$ 2 years ago $\rightarrow$ Control/Exclude.
  - Not Use.

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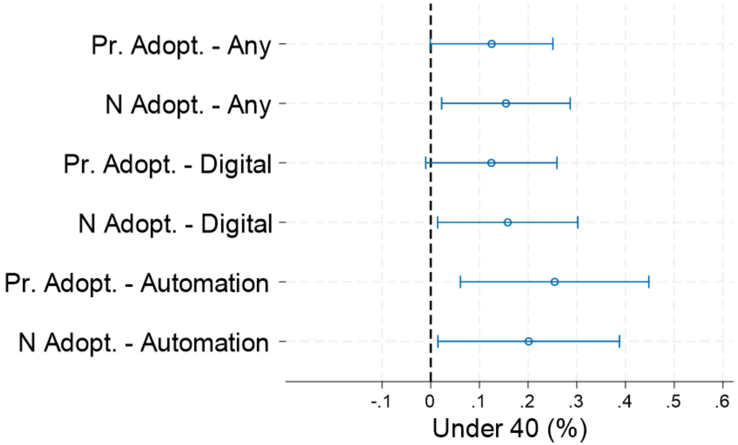
Young Workforce Predicts Higher Adoption



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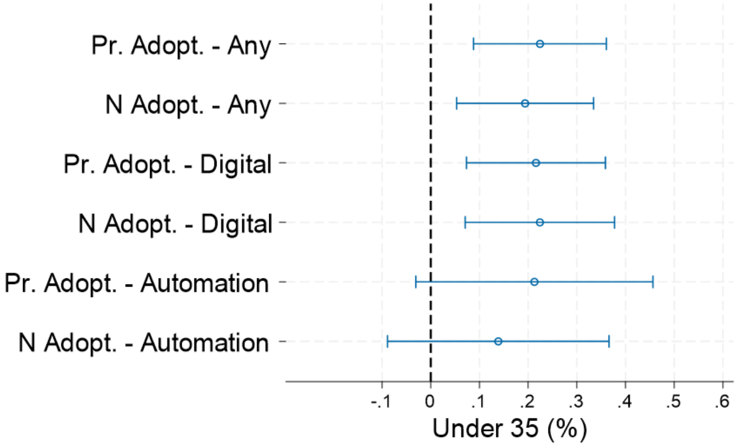

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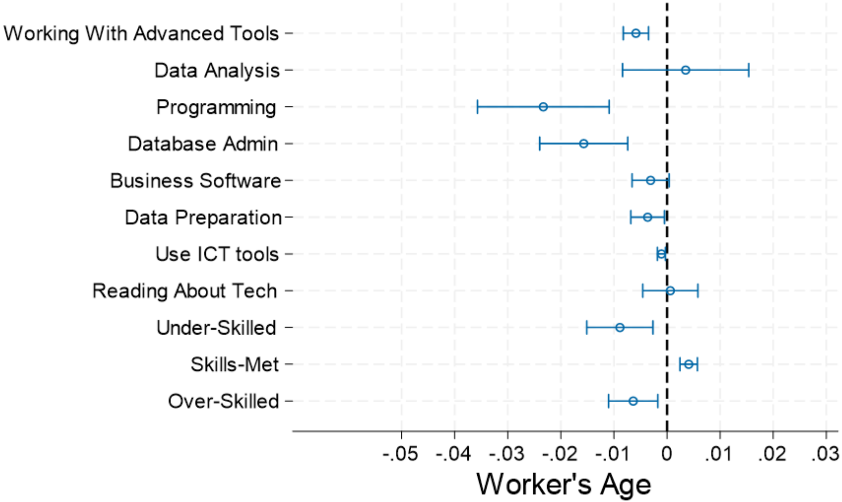
Young Perform More Tech-Related Tasks



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Young Report Productivity Gains for Tech Adoption

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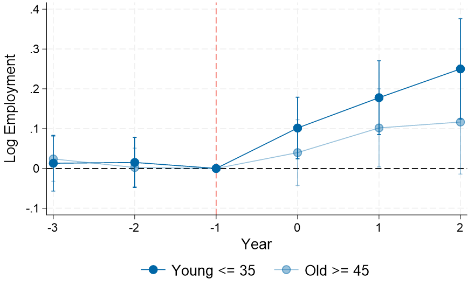
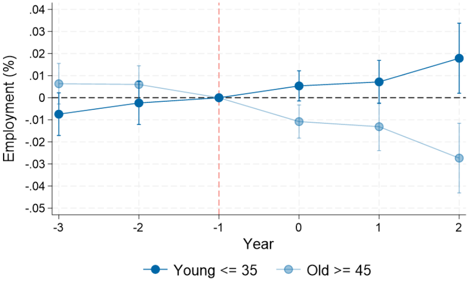
Event Study - Employment Share



(a) Log Employment



(b) Employment Share

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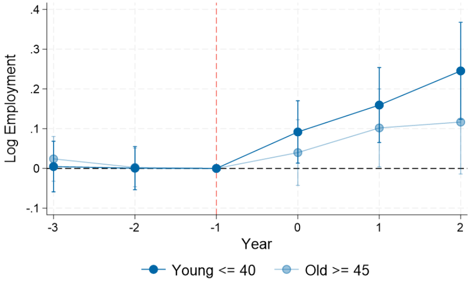
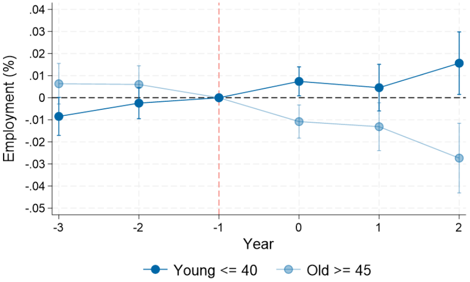
Event Study - Under 40



(a) Log Employment



(b) Employment Share

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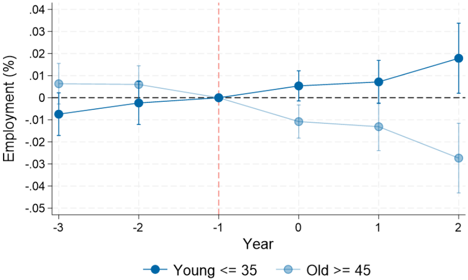
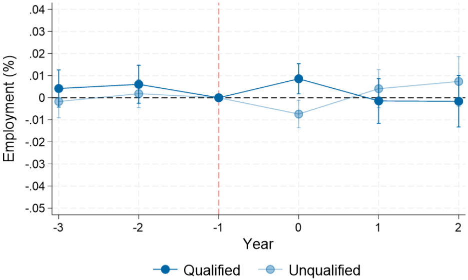
Event Study - College Heterogeneity



(a) Age Heterogeneity



(b) College Heterogeneity

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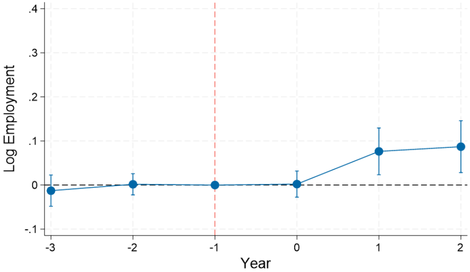
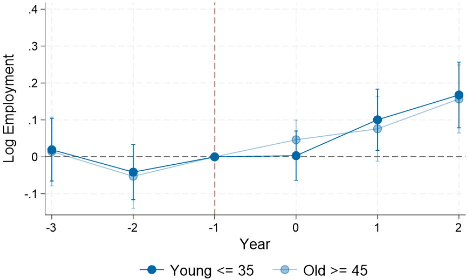
Event Study - Automation Technologies



(a) Log Employment



(b) Age Heterogeneity

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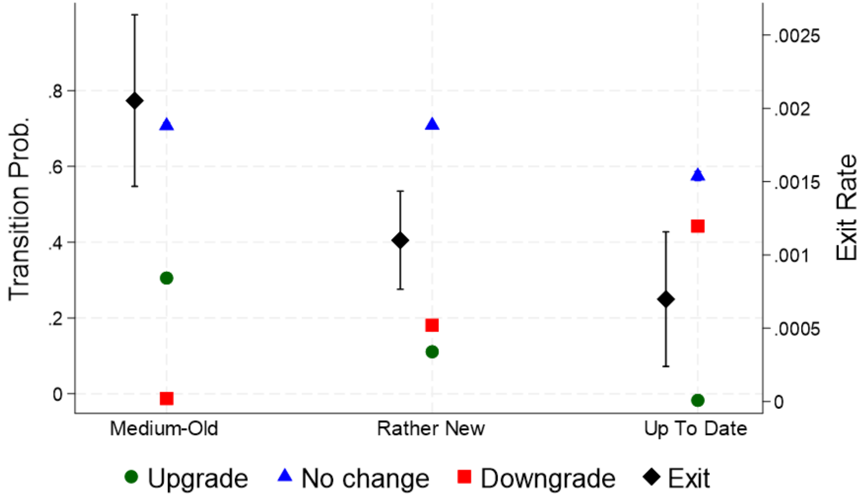
Tech Transition in the Data



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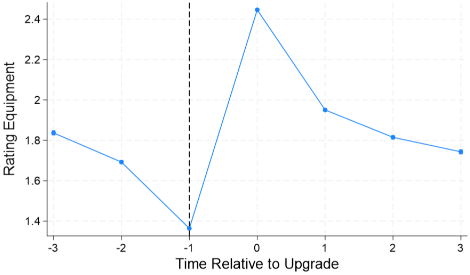
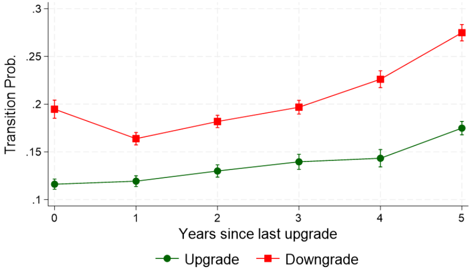
Cyclicality of Tech Upgrade



(a) Equipment Rating



(b) Upgrade - Downgrade

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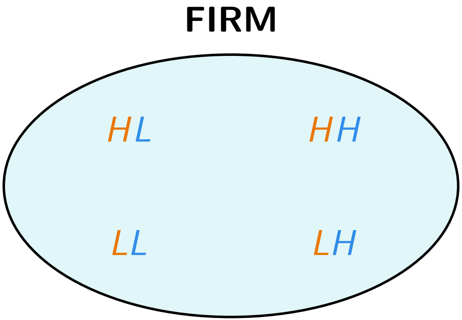
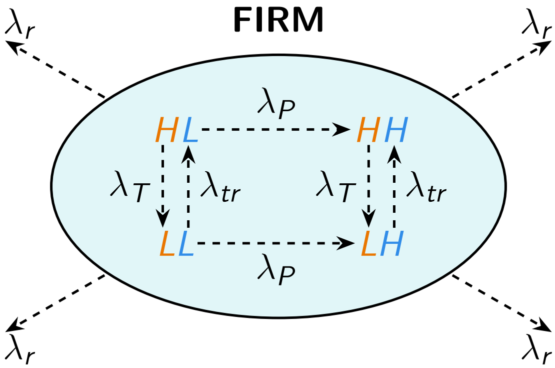
Firms' Workforce



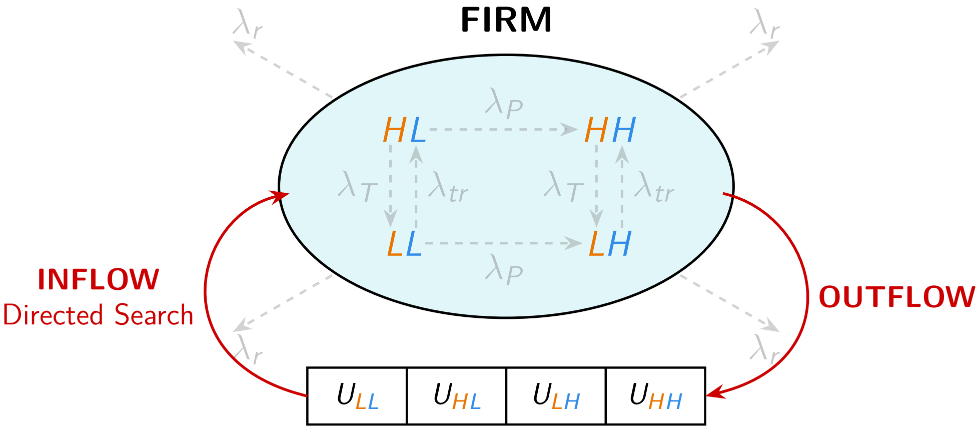
- A firm is a collection of workers of different types.

Firms' Workforce



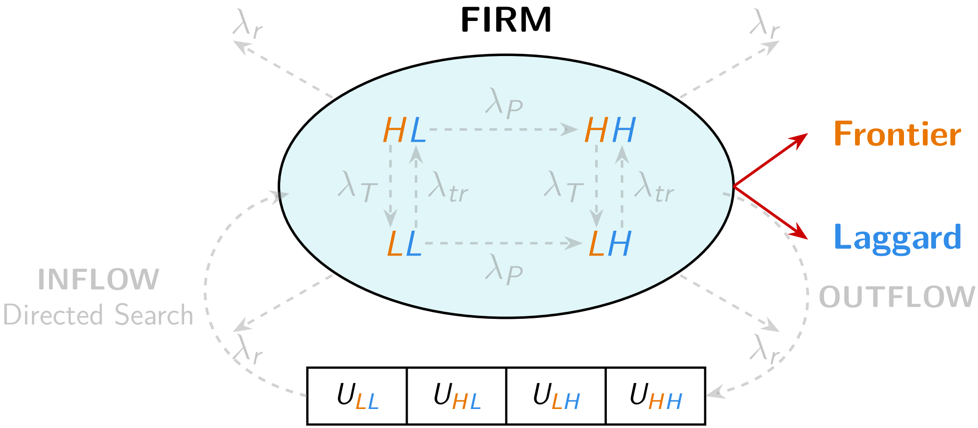
- Workers transitions: obsolescence, experience, up-skilling, retirement.

Firms' Workforce



- Inflows: type-specific hiring from unemployment.
- Outflows: Endogenous + Exogenous separations.

Firms' Workforce



- Technology Choice: skill-mix of incumbents + availability of skills from U

Unemployed Workers

The value of an unemployed worker of type $i \in \mathcal{S}$ is

$$(\rho+\lambda^r)\mathcal{U}_i = \max_W \Big\{ b + \underbrace{\mu_i(W)}_{\text{Job Finding Rate}} \max\{W - \mathcal{U}_i, 0\} + \underbrace{\lambda_T(\mathcal{U}_{L,s_P} - \mathcal{U}_{H,s_P})}_{\text{Tech Obsolescence}} \underbrace{\mathbb{1}\{s_T = H\}}_{\text{High-tech Worker}} \Big\}$$

$$\implies \mu_i(W) = \frac{(\rho+\lambda^r)\mathcal{U}_i - b - \lambda_T(\mathcal{U}_{L,s_P} - \mathcal{U}_{H,s_P})\mathbb{1}\{s_T = H\}}{W - \mathcal{U}_i}, \qquad s_P \in \{L, H\}$$

Trade-off: job-finding rate is **inversely related** to the contract's promised value W

- $W \uparrow \implies$ submarket (i, W) attracts more workers $\implies \mu_i(W) \downarrow$, wait time $\uparrow$
- Continuum of active submarkets maximizing unemployment value.

Potential Entrants

- Potential entrants' value:

$$J^e = \underbrace{-\kappa}_{\text{Entry Cost}} + \underbrace{p_0 \tilde{J}^e(\tau = 0) + (1 - p_0)\tilde{J}^e(\tau = 1)}_{\text{Expected Profits}}$$

  - Pay a flow cost to open a business: κ
  - Enter as frontier with probability p_0.

- Upon entry:

$$\tilde{J}^e(\tau) = \sum_z F^e(z)\left[\max_{\{W_i'\}} \sum_{i \in \mathcal{S}} \eta_i \left(W_i'(s_i^e)\right) J(s_i^e)\right], \ \forall i$$

  - Draw a **random productivity shock** from F_z^e
  - **Post one vacancy** for each type of worker, choosing the submarket W_i.

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Key Property of the Problem

- Assume:
  1. Utilities are linear and transferrable across agents
  2. Contract space is complete: state-contingent contracts
  3. Directed search
- Define the **Joint Surplus**: $\Sigma(\overrightarrow{n}, z, \tau) \equiv \underbrace{J(\overrightarrow{s})}_{\text{Firm's Value}} + \sum_i n_i \underbrace{W_i}_{\text{Worker's Value}}$

Proposition (Schaal [2017])

Solving the firm's problem is equivalent to maximize to joint surplus over the simpler contract space:

$$\mathcal{C}^{\Sigma} = \left\{ \{ \underbrace{v_i}_{\text{Recruitment}}, \underbrace{\delta_i}_{\text{Firing}}, \underbrace{W_i'(s_i^+)}_{\text{Continuation Promise}} \}_{i \in \mathcal{S}}, \underbrace{\pi_e}_{\text{Re-training}}, \underbrace{a_{\mathcal{T}}}_{\text{Tech Investment}} \right\}$$

The joint surplus doesn't depend on promised utilities: new state space: $s = (\vec{n}, z, \tau)$

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Notation: Evolution of State Variables

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Remark: Given continuous time, only one state transition can happen simultaneously.

$$\vec{s}' \equiv (\vec{n}, z', \tau') \in \begin{cases} (n_{LL}+1, \vec{s}_-),\ (n_{LH}+1, \vec{s}_-),\ (n_{HL}+1, \vec{s}_-),\ (n_{HH}+1, \vec{s}_-) & \text{Hiring } i: \ \vec{s}_i^{\,+},\ \forall i \\ (n_{LL}-1, \vec{s}_-),\ (n_{LH}-1, \vec{s}_-),\ (n_{HL}-1, \vec{s}_-),\ (n_{HH}-1, \vec{s}_-) & \text{Firing } i: \ \vec{s}_i^{\,-},\ \forall i \\ (n_{LL}-1, n_{HL}+1, \vec{s}_-),\ (n_{LH}-1, n_{HH}+1, \vec{s}_-) & \text{Up-skilling}: \ \vec{s}_{\pi_e} \\ (n_{HL}-1, n_{LL}+1, \vec{s}_-),\ (n_{HH}-1, n_{LH}+1, \vec{s}_-) & \text{Obsolescence}: \ \vec{s}_{\lambda_T} \\ (n_{LL}-1, n_{LH}+1, \vec{s}_-),\ (n_{HL}-1, n_{HH}+1, \vec{s}_-) & \text{Experience}: \ \vec{s}_{\lambda_R} \\ (n_{LL}-1, \vec{s}_-),\ (n_{LH}-1, \vec{s}_-),\ (n_{HL}-1, \vec{s}_-),\ (n_{HH}-1, \vec{s}_-) & \text{Retirement}: \ \vec{s}_{\lambda_o} \\ (\tau', \vec{s}_-) & \text{Tech Change}: \ \vec{s}_{\tau'} \\ (z', \vec{s}_-) & \text{Prod. Shock}: \ \vec{s}_{z'} \end{cases}$$

Firm's Problem

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- Long-Term Contract: $\overrightarrow{\mathcal{C}} = \left\{ \{w_i, v_i, \delta_i, W_i'(\overrightarrow{s})'\}_{i\in\{LL,LH,HL,HH\}},\ \pi_e,\ a_\tau \right\}$

$$\rho J(\overrightarrow{s}) = \max_{\overrightarrow{\mathcal{C}}} \left\{ y - C_e(\pi_e)(n_{LL}+n_{LH}) - C_\tau(a_\tau) + s^F \left(J^e - J(\overrightarrow{s})\right) \right.$$

$$\textit{Workforce Costs} \quad - \sum_i \left[w_i n_i + C_{\delta_i}(\delta_i) n_i + C_{v_i}(v_i) \right]$$

$$\textit{Hiring} \quad \left. + \sum_i v_i \eta_i \left(W_i'(\overrightarrow{s}_i^{+})\right) \left(J(\overrightarrow{s}_i^{+}) - J(\overrightarrow{s})\right) \right\}$$

$$\textit{Separations} \quad + \sum_i \left(\delta_i + s_i^W\right) n_i \left(J(\overrightarrow{s}_i^{-}) - J(\overrightarrow{s})\right) + \sum_i \lambda_r n_i \left(J(\overrightarrow{s}_{\lambda_o}) - J(\overrightarrow{s})\right)$$

$$\textit{Skill Change} \quad + \sum_{i\in\{LL,LH\}} \pi_e \left(J(\overrightarrow{s}_{\pi_e}) - J(\overrightarrow{s})\right) + \sum_{i\in\{HL,HH\}} \lambda_T \left(J(\overrightarrow{s}_{\lambda_T}) - J(\overrightarrow{s})\right) + \sum_{i\in\{LL,HL\}} \lambda_P \left(J(\overrightarrow{s}_{\lambda_P}) - J(\overrightarrow{s})\right)$$

$$\textit{Tech Change} \quad + \sum_{\tau'} \pi(\tau'|\tau, a) \left(J(\overrightarrow{s}_{\tau'}) - J(\overrightarrow{s})\right)$$

$$\textit{Prod. Shock} \quad \left. + \sum_{z'} F_z(z'|z) \left(J(\overrightarrow{s}_{z'}) - J(\overrightarrow{s})\right) \right\} \quad \text{s.t.} \quad \mathcal{W}_i(\overrightarrow{\mathcal{C}}) \geq W_i, \quad W_i' \geq \mathcal{U}_i, \quad \forall i$$

Joint Surplus Maximization

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$$(\rho + s^F)\Sigma(s) = \max_{\mathcal{C}^\Sigma} \Big\{ y - C_e(\pi_e)(n_{LL} + n_{LH}) - C_\tau(a_\tau) - \sum_i \Big[C_{\delta_i}(\delta_i) n_i + C_{v_i}(v_i) \Big]$$

Outside Option $+ \sum_i n_i \left(\delta_i + s_i^W + s^F\right) \mathcal{U}_i$

Utility to New Hires $- \sum_i v_i \eta_i \left(W_i'(s_i^+)\right) W_i'(s_i^+)$

Hiring $+ \sum_i v_i \eta_i \left(W_i'(s_i^+)\right) \left(\Sigma(s_i^+) - \Sigma(s)\right)$

Separations $+ \sum_i \left(\delta_i + s_i^W\right) n_i \left(\Sigma(s_i^-) - \Sigma(s)\right) + \sum_i \lambda_r n_i \left(\Sigma(\vec{s}_{\lambda_o}) - \Sigma(\vec{s})\right)$

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Tech Change $+ \sum_{\tau'} \pi(\tau' | \tau . a_\tau)(\Sigma(s_{\tau'}) - \Sigma(s))$

Prod. Shock $+ \sum_{z'} F_z(z'|z)(\Sigma(s_{z'}) - J(s)) \Big\}$

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Separations $$+ \sum_i \left(\delta_i + s_i^W\right) n_i \left(\Sigma(s_i^-) - \Sigma(s)\right) + \sum_i \lambda_r n_i \left(\Sigma(\vec{s}_{\lambda_o}) - \Sigma(\vec{s})\right)$$

Skill Change $$+ \sum_{i \in \{LL,LH\}} \pi_e \left(\Sigma(\vec{s}_{\pi_e}) - \Sigma(\vec{s})\right) + \sum_{i \in \{HL,HH\}} \lambda_T \left(\Sigma(\vec{s}_{\lambda_T}) - \Sigma(\vec{s})\right) + \sum_{i \in \{LL,HL\}} \lambda_P \left(\Sigma(\vec{s}_{\lambda_P}) - \Sigma(\vec{s})\right)$$

Tech Change $$+ \sum_{\tau'} \pi(\tau' | \tau . a_\tau)(\Sigma(s_{\tau'}) - \Sigma(s))$$

Prod. Shock $$+ \sum_{z'} F_z(z'|z)(\Sigma(s_{z'}) - J(s)) \Big\}$$

Aggregate Productivity Decomposition

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Aggregate productivity

$$
\begin{aligned}
\frac{\mathcal{Y}}{E} &= \frac{1}{E}\sum_{s\in\mathcal{S}} y^*(s)f(s) \\
&= \frac{F}{E}\sum_{z,\tau}\frac{F_{z,\tau}}{F}\sum_{n} y^*(s)\tilde{f}_{z,\tau}(n) \\
&= \underbrace{\left(\frac{F}{E}\right)^{1-\nu}}_{\text{Firm Size}}\sum_{z,\tau}\underbrace{\frac{F_{z,\tau}}{F}}_{\text{Firm Selection}}\underbrace{\sum_{\hat{n},m} y^*_{z,\tau}(\hat{n},m)g_{z,\tau}(\hat{n},m)}_{\text{Workers Allocation}}
\end{aligned}
\tag{1}
$$

where

$$
g_{z,\tau}(\hat{n},m) = \sum_{n}\tilde{f}_{z,\tau}(n)\mathbb{I}\left\{\frac{n}{E/F} = \hat{n} \;\;\&\;\; m_\tau = m\right\}
$$

Calibration Strategy

- New Entrant Workers
  - Model: HL w.p. ω; LL w.p. $1-\omega$.
  - Data: HL if college (C); LL otherwise (NC).
- Exog. Skill Transitions: $\lambda_T, \lambda_E \implies$ Life-Cycle Wage Profiles.
  - **High** λ_E: Faster early growth for NC + Flattening earlier in life.
  - **High** λ_T: Slower early growth for C + Faster decrease of college premium.
- Endog. Skill Transitions: λ_{tr}
  - Calibrate the **cost of training** to info on on-the-job training participation within firms.

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Calibration Strategy

- Skill Complementarity: φ
  - Correlation between within firm wage-dispersion and age dispersion.
- Task weights: α_τ
  - Match event study regressions upon adoption.
- Efficiency Units: γ_T^H, γ_T^L, γ_E^L
  - **High** $\frac{\gamma_T^H}{\gamma_T^L}$: Larger Wage dispersion early in life.
  - **High** $\frac{\gamma_E^H}{\gamma_E^L}$: Higher Level growth of NC.
  - **High** $\frac{\gamma_E^H}{\gamma_T^H}$: Higher Level growth of C.

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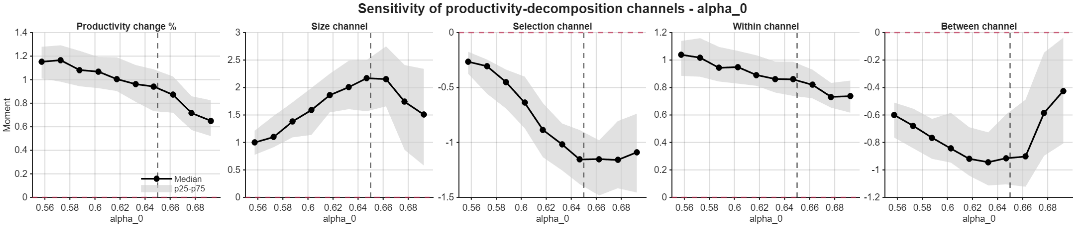
Simulation of Productivity Decomposition: α_0

- α_0: Weight of Tech-Skills in Frontier Production.



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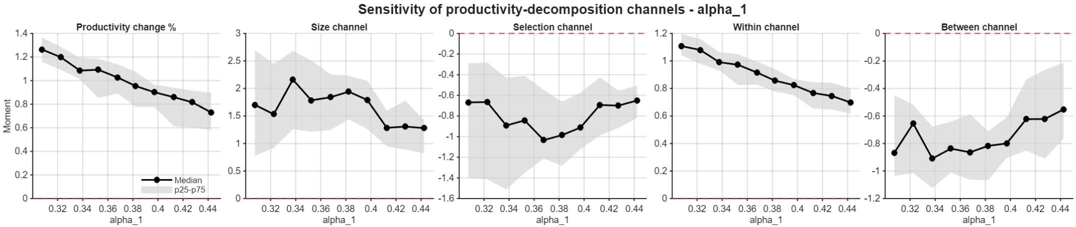
Simulation of Productivity Decomposition: α_1



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Aging, Skill Composition and Technology Adoption

- Low Training Cost + **Skill Substitutes** $\implies$ Very Little Effect.