Automation and the Future of Work: Assessing the Role of Labor Flexibility

(joint with Andrea Manera)

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Research Questions and Main Idea

We ask the following questions:

1. Will labor survive in production jobs at risk of automation?
2. If so, what will those jobs look like?
3. How do automation and labor market institutions interact?

Our idea:

- Labor flexibility, **in hiring and firing**, as a comparative advantage
- Demand for flexibility if investment is costly and environment is unpredictable

Plan of the Talk

1. Motivation and Literature Review
2. Theoretical Analysis:
   - The Firm Problem
   - Partial Equilibrium
3. Quantitative Analysis:
   - Multi-Sector Model in General Equilibrium
   - Calibration
   - Comparative Statics
4. Extension with Rigid Labor
5. Conclusions

Tesla's Model 3 "Production Hell"

Tesla's Model 3: Expectations

Tesla's Model 3: Reality

"Accelerated Hiring" during Covid-19

Company news

Amazon has hired 175,000 additional people

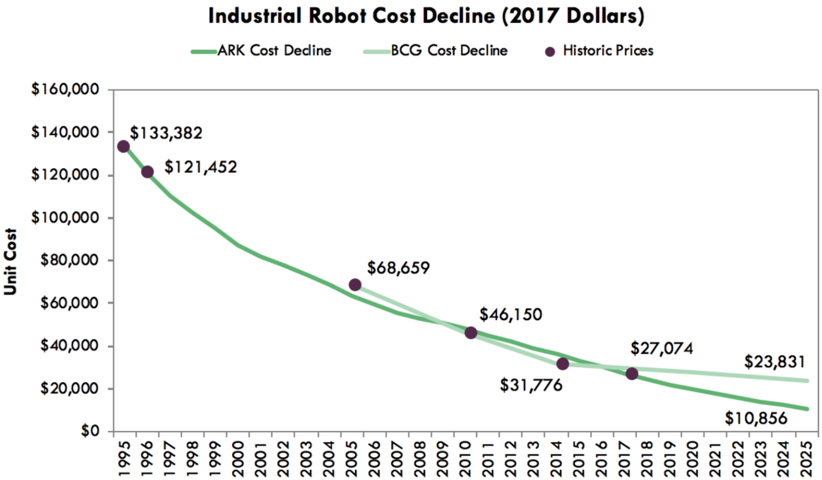
The company has brought on 175,000+ new associates during the COVID-19 pandemic.

Coronavirus is here, and we need your help.

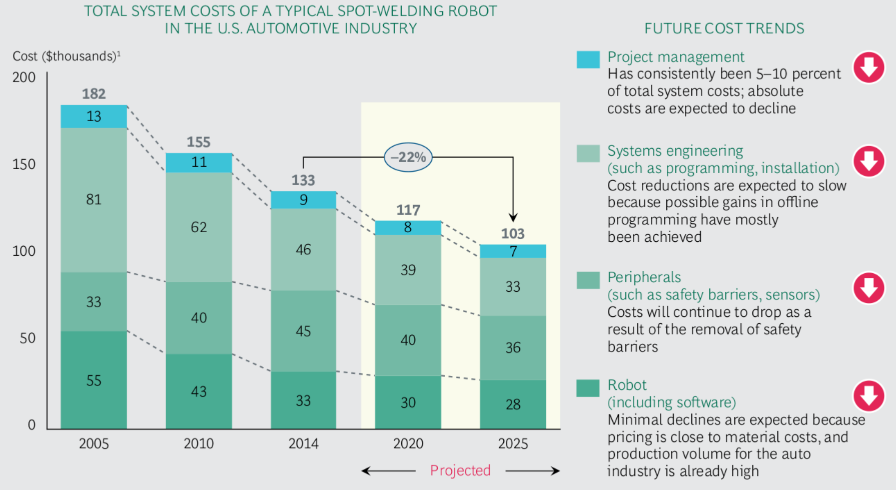
In response to the urgent and increased health care needs of Americans impacted by the COVID-19 pandemic, CVS Health is accelerating a plan to fill more than 50,000 full-time and part-time positions across the country.

We have a significant demand for professionals across the company, including: full- and part-time, short- or long-term temporary or temp-to-hire Retail Store Associates, Warehouse Distribution Workers, Customer Service Representatives, Pharmacy Technicians, Registered Nurses, Nurse Practitioners, Licensed Vocational Nurses, Licensed Professional Nurses, Pharmacists, Corporate Professionals.

Improvements in Robotic Technology (ARK Investment, 2019)



Cost Breakdown for Robot Installation (BCG, 2019)



Relevant Literature

1. *Automation*
   - Labor or Capital Augmenting: Bessen (2019), Sachs and Kotlikoff (2012), Sachs et alii (2015), Nordhaus (2015), Berg et alii (2018)
   - Task-Based Framework: **Acemoglu and Restrepo (2018a,b,c,d)**, Graetz and Michaels (2018)
2. *Investment*
   - Jorgenson (1963), Abel (1983), Pindyck (1988, 1991), Caballero (1991), Dixit and Pindyck (1994), **Abel and Eberly (1996, 1997)**, Stokey (2009)
3. *Related Empirical Evidence*
   - Employment $\downarrow$ at Commuting Zone / Sector level:
     Acemoglu et alii (2018, 2020), Dauth et alii (2019)
   - Employment $\uparrow$ at adopting firms' level:
     Acemoglu et alii (2020), Bonfiglioli et alii (2020), Koch et alii (2019), Aghion et alii (2019)

How Do We Differ?

Literature:

- Robots are adjusted flexibly; there is a rental market for robots;
- Environment is deterministic;
- Infinite substitution $\rightarrow$ full automation if robots are cheap enough;

This paper:

- adjustment costs; robots are owned and not rented on the market;
- idiosyncratic volatility;
- even with infinite substitution and cheap robots, labor still used

Static Maximization

- Homogeneous firms maximize profits, by investing in robots R and hiring labor L
- Production function is:

$$Q\left(L, R, u, z\right) = z\left(\Gamma L + \left(1 - \Gamma\right) uR\right)^{\theta}$$

- Notation
  - R robot stock in place
  - L labor (can be hired in spot markets)
  - u utilization rate of machines
  - θ decreasing returns
  - z idiosyncratic shock (demand or productivity)
  - Γ relative MRTS

Static Maximization

- In the short run, robot stock is given. Choose:
  - How much labor to employ
  - Robot utilization rate
- Solve:

$$\max_{L \geq 0, 0 \leq u \leq 1} \; pz \left(\Gamma L + (1 - \Gamma) \, uR \right)^{\theta} - wL - muR$$

- Make the problem interesting. Flow labor savings are strictly positive:

$$\Omega \equiv \frac{1 - \Gamma}{\Gamma} w - m > 0$$

Static Maximization

- Solution:

$$L^{\star}(R,z)=\begin{cases}\frac{1-\Gamma}{\Gamma}\left(\bar{R}(z)-R\right) & R\leq\bar{R}(z)\\ 0 & R>\bar{R}(z)\end{cases}$$

$$u^{\star}(R,z)=\begin{cases}1 & R\leq\hat{R}(z)\\ \frac{\hat{R}(z)}{R} & R>\hat{R}(z)\end{cases}$$

- Cutoffs

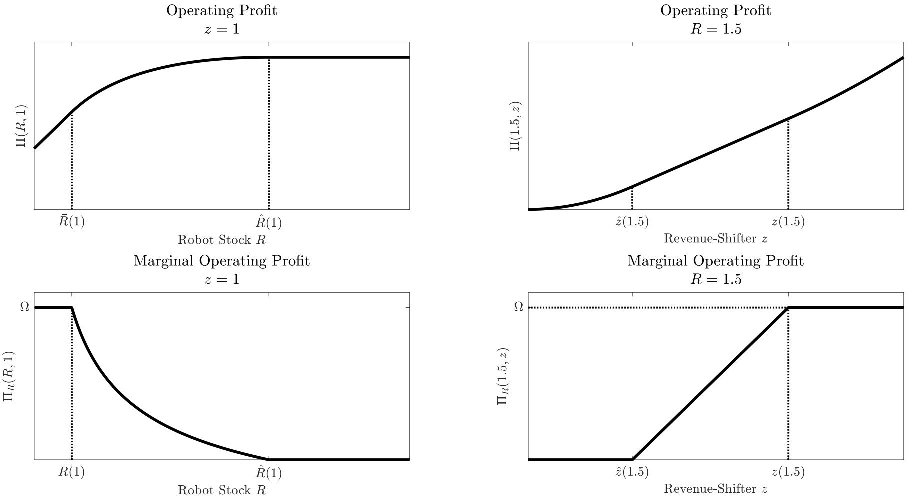
$$\underbrace{\bar{R}(z)=\frac{1}{1-\Gamma}\left(\frac{pz\theta\Gamma}{w}\right)^{\frac{1}{1-\theta}}}_{\text{Full Automation Cutoff}}\qquad\underbrace{\hat{R}(z)=\frac{1}{1-\Gamma}\left(\frac{pz\theta(1-\Gamma)}{m}\right)^{\frac{1}{1-\theta}}}_{\text{Optimal Scale for Flow Costs } m}$$

The Operating Profit Function

- (Static) Profit Function:

$$\Pi(R,z) = \begin{cases} \underbrace{(1-\theta)\, pz\,(1-\Gamma)^{\theta}\,\bar{R}(z)^{\theta}}_{\text{Maximum profits using only labor}} + \underbrace{\Omega R}_{\text{Linear labor savings}} & R \leq \bar{R}(z) \\ \underbrace{pz\,(1-\Gamma)^{\theta}\,R^{\theta} - mR}_{\text{Not profitable to hire labor, but still undersized}} & \bar{R}(z) < R < \hat{R}(z) \\ \underbrace{pz\,(1-\Gamma)^{\theta}\,\hat{R}(z)^{\theta} - m\hat{R}(z)}_{\text{Maximum profits achieved when } R \text{ can be rented}} & \hat{R}(z) < R \end{cases}$$

Operating Profit and Marginal Operating Profit



The Investment Problem

- Firms solve: Robustness

$$
\begin{aligned}
V\left(R_0, z_0\right) \equiv \max_{I_t} \quad & \mathbb{E}_0\left[\int_0^{\infty} \exp\{-\rho t\}\left(\Pi\left(R_t, z_t\right) - p_R I_t - \frac{\psi_R}{2} I_t^2\right) \mathrm{d}t\right] \\
\text{s.t.} \quad & \mathrm{d}R_t = \left(I_t - \delta R_t\right) \mathrm{d}t, \\
& \mathrm{d}z = \mu\left(z_t\right) \mathrm{d}t + \sigma\left(z_t\right) \mathrm{d}W, \\
& R_0, z_0 \text{ given.}
\end{aligned}
$$

- HJB Equation:

$$
\rho V(R, z) = \max_{I \in \mathbb{R}} \Pi(R, z) - p_R I - \frac{\psi_R}{2} I^2 + (I - \delta R) V_R(R, z) + \mu(z_t) V_z(R, z) + \frac{\sigma^2(z_t)}{2} V_{zz}(R, z)
$$

- Diffusion process satisfies “FOSD Property”:

$$
z_t' \geq z_t \implies F\left(z_{t+s} \mid z_t'\right) \succeq_{FOSD} F\left(z_{t+s} \mid z_t\right)
$$

The Investment Policy Function

FOC for investment

$$I^{\star}(R,z) = \frac{1}{\psi_R}\left(V_R(R,z) - p_R\right)$$

Proposition

Under mild regularity conditions, the investment policy function is:

- *non-increasing in R for all z*
- *non-decreasing in z for all R*
- *non-decreasing in w for all R, z*
- *bounded from above by:*

$$\frac{1}{\psi_R}\left[\frac{\Omega}{\rho+\delta} - p_R\right]$$

Intuition

- Simple Observation (Envelope Theorem)

$$
\begin{aligned}
V_R(R_0, z_0) &= \mathbb{E}_0\left[\int_0^\infty \exp\{-(\rho+\delta)t\}\,\Pi_R(R_t, z_t)\,\mathrm{d}t \mid (R_0, z_0)\right] \\
&\leq \int_0^\infty \exp\{-(\rho+\delta)t\}\,\Omega\mathrm{d}t \\
&= \frac{\Omega}{\rho+\delta}
\end{aligned}
$$

- Interpretation:
  - marginal returns are capped because of the labor substitution margin
  - willingness to pay to install and/or maintain robots is limited
- Assume (to make the problem interesting):

$$
p_R < \frac{\Omega}{\rho+\delta}
$$

The Desired Robot Stock

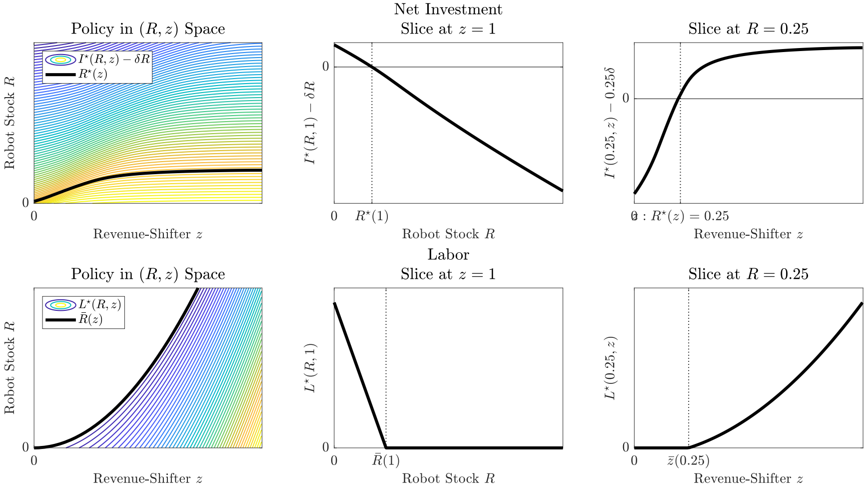
- Define $R^{\star}(z)$, $\forall z$, as

$$I^{\star}\left(R^{\star}(z), z\right) = \delta R^{\star}(z)$$

- Interpretation: $R^{\star}(z)$ as "desired robot stock" if $z_t = z$ forever
- Also, recall the Full Automation Cutoff:

$$\bar{R}(z) = \frac{1}{1-\Gamma}\left(\frac{pz\theta\Gamma}{w}\right)^{\frac{1}{1-\theta}}$$

Policy Functions



Main Result (No Full Automation)

- Note:

$$R^{\star}(z) \leq R^{\star}_{\max} \equiv \frac{1}{\psi_R \delta}\left[\frac{\Omega}{\rho+\delta} - p_R\right]$$

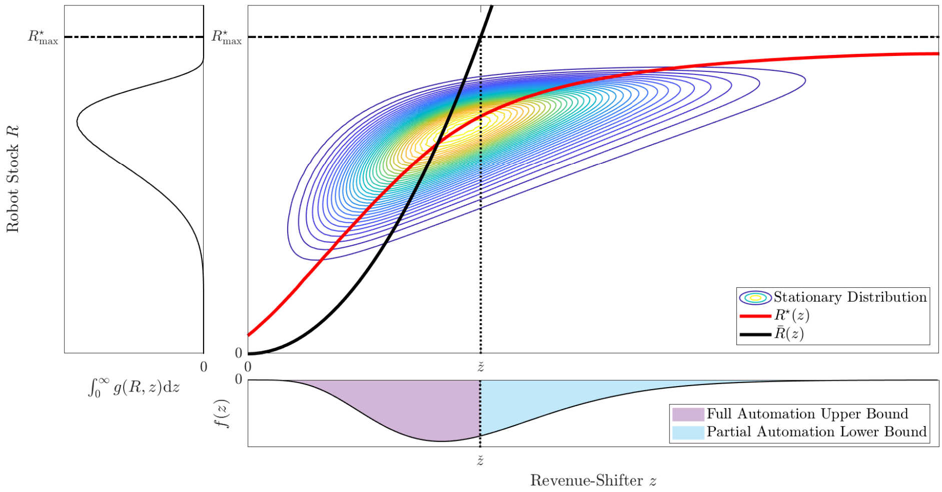
- Ergodic set for R is bounded from above!
- Moreover, given $\bar{R}(z)$, there is a lower bound on labor
- If $\delta > 0$, we show that the stationary distribution has support within:

$$\left[R^{\star}(z_{\min}), R^{\star}_{\max}\right] \times \mathcal{Z}$$

Proposition

For any purchase price of robots p_R, as long as $\delta > 0$, there exists a finite value of the adjustment cost parameter ψ_R such that the stationary distribution $G(R, z)$ does not feature full automation.

Stationary Distribution and Bounds to Full Automation



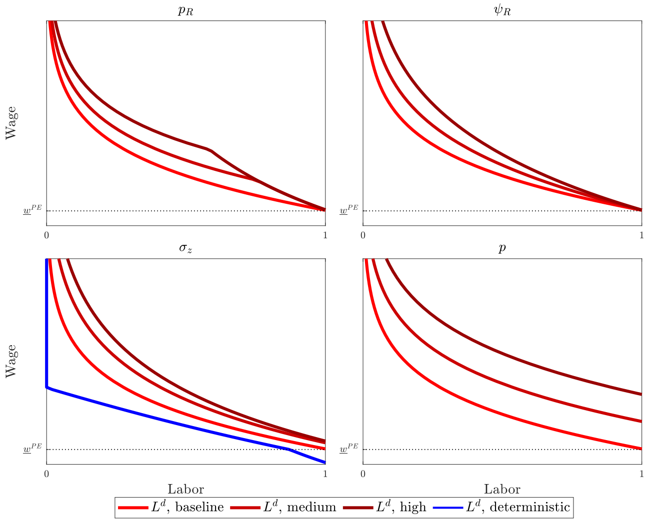
Characterization

- Consider ergodic distribution $F(z)$ for the revenue shock.
- Define $\check{z}$ as highest shock s.t. firms with $R = R^{\star}_{\max}$ *do not hire labor,*

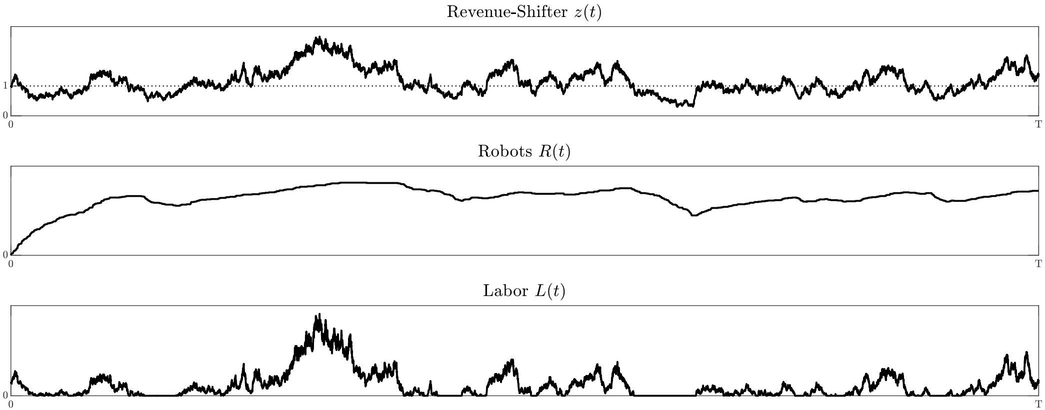
$$\begin{aligned} \check{z} &\equiv \bar{R}^{-1}\left(R^{\star}_{\max}\right) \\ &= \frac{w}{p\theta\Gamma}\left[\frac{1-\Gamma}{\delta\psi_R}\left(\frac{\Omega}{\rho+\delta} - p_R\right)\right]^{1-\theta}. \end{aligned}$$

- Then, $F(\check{z})$ is the *upper bound to the mass of firms automating fully*
- $1 - F(\check{z})$ is the *lower bound of the mass of firms hiring labor*

Aggregate Labor Demand Comparative Statics



Firm-Level Dynamics



Summary of Predictions

- Aggregate Labor Demand:
  - decreases with a *fall* in the price of robots
  - decreases if adjustment costs are *lower*
  - increases the larger is the variance of the shock
- Firm Level:
  - Demand for labor can increase while firm is investing in robots
  - More productive firms install more robots *in the steady state*
  - Labor is hired in "bursts" to cope with positive shocks
- Fits qualitatively with empirical literature we cited above

Multi-Sector Equilibrium

1. Calibrate parameters using evidence on robot penetration and price:
   - 13 macro-sectors defined by the International Federation of Robotics (IFR)
     - $\approx$SIC 2-digits (Automotive, Textiles, Electronics etc)
   - Price of robot relative to one production line employee wage (from BCG and OES)
2. Assess quantitatively the importance of advances in robotic technology:
   - Price p_R
   - Relative productivity Γ
   - Versatility and ease of (re-)deployment ψ_R

Intermediate Goods

Output of each sector (e.g., automotive) is aggregate from continuum of firms described above:

$$x_s \equiv \int Q\left(L_s^\star(R,z), R, u_s^\star(R,z), z\right) \mathrm{d}G_s(R,z) \qquad \forall s$$

Firms **within each sector** face the same:

- price p_s for their good
- θ_s
- $\sigma_{z,s}$,$\theta_{z,s}$ parameters of CIR stochastic process
- Γ_s

Firms **across all sectors** face the same:

- equilibrium wage w
- adjustment cost ψ_R
- maintenance cost $m = 0$

Final Good

Representative firm produces with Cobb-Douglas aggregate of the 13 intermediate goods (Oberfield and Raval, 2014)

$$Y = A_F \prod_{s=1}^{13} x_s^{\xi_s}$$

- $\sum_{s=1}^{13} \xi_s = 1 \rightarrow$ shares of manufacturing value added of each sector
- A_F aggregate TFP

Household

Hand-to-mouth representative households with GHH preferences over consumption and labor.

- Labor Supply:

$$\ell^{\star} = \left(\frac{w}{\chi}\right)^{\varphi}$$

- Demand for Final Good:

$$c^{\star} = w\ell^{\star} + \Psi + \Pi$$

Note: interest rate r is **exogenously fixed** (at $r = \rho = 4\%$)

Equilibrium

Prices $\left(w, (p_s)_{s=1}^{13}\right)$ clear all markets:

- **Labor Market**:

$$\ell^\star = \sum_{s=1}^{13} \int_0^\infty L_s^d \left(R, z\right) dG_s \left(R, z\right)$$

- **Intermediate Goods**:

$$x_s = \xi_s \frac{Y/A^F}{p_s} \qquad \forall s = 1, \ldots, 13$$

- **Final Good:** excluded by Walras Law, numéraire

Note: robot sector is excluded and p_R/w is **exogenous**.

Multi-Sector Equilibrium: Limit Case

- Most (if not all) firms today are *not* fully automated!
- Model is analytically tractable in this limit case $\left(F_s\left(\check{z}_s\right) \approx 0\right)$
- Can show almost all firms *within each sector* choose the sector-specific stock:

$$R \approx R^{\star}_{\max,s} = \frac{1}{\psi_R \delta}\left[\frac{\Omega_s}{\rho+\delta} - p_R\right]$$

Proposition

Consider the general equilibrium model with $F_s\left(\check{z}_s\right) \to 0$, $\theta_s = \theta$ for all s, and elasticity of substitution across industries $\sigma = 1$. In the neighborhood of an equilibrium supported by prices (w, p), aggregate equilibrium labor is increasing in m, p_R and ψ_R, and aggregate robot penetration is decreasing in m, p_R and ψ_R.

Calibration Strategy

- Parameters obtained from data directly:

$$\left(\frac{p_R}{w}\right)_{2010}, \left(\frac{p_R}{w}\right)_{2014}, \delta, \rho$$

- Parameters calibrated by directly matching a moment:
  - ξ_s: share of manufacturing value added from BEA
  - θ_s: average production line employees' share of manufacturing VA before 1980
- Other parameters:
  - $\sigma_{z,s}, \theta_{z,s}$: fit CIR process by ML on TFP residual from Compustat Data Details
  - ψ_R/w: match increase in aggregate robot adoption between 2010 and 2014, assuming limit case Details
  - Γ_s: given ψ_R/w, match penetrations in each sector in 2014 Details

Do the Parameter Values Make Sense? Untargeted Moments

- Parameter values: ▸ Constant-Across-Sectors Parameters ▸ Sector-Specific Parameters
- Magnitude of adjustment cost parameter:
  - For automotive sector, ratio of adj costs to purchase price in steady state is:

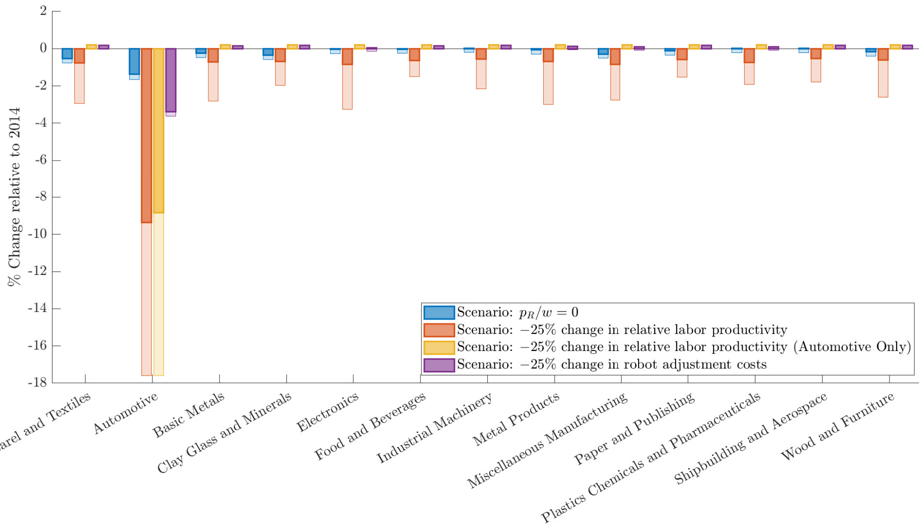
$$\frac{\Psi\left(\delta R^{\star}_{\text{max,auto}}\right)}{p_R \delta R^{\star}_{\text{max,auto}}} = \frac{\psi_R \delta}{2 p_R} \times \left(\frac{R}{L}\right)_{2014,\text{auto}} \times \frac{L_{\text{auto}}}{1000} \approx 3.2917$$

  while from 2014 data on arc-welding mechanical arms we get ≈ 3.03
- Semi-Elasticity of aggregate labor with respect to robot penetration
  - ranges between 0.01% and 0.1%, depending on the underlying source
  - ballpark of 0.2% from Acemoglu and Restrepo (2019)

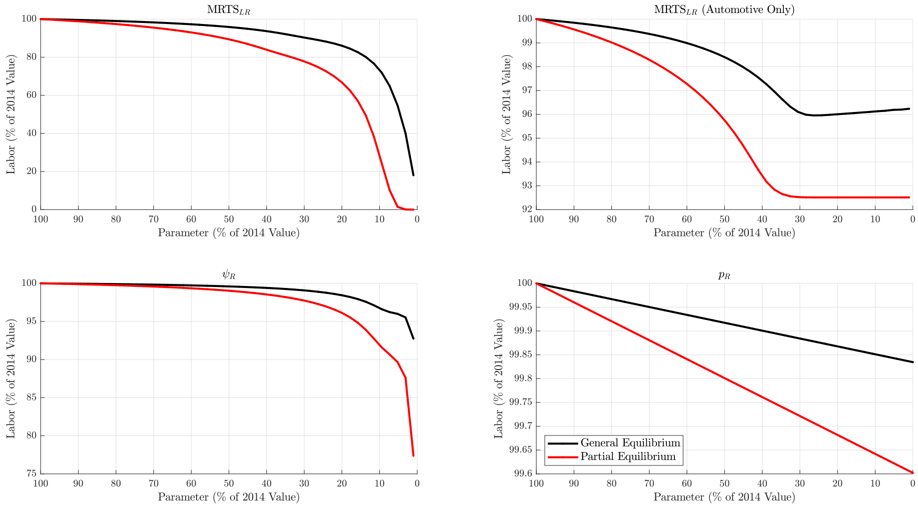
Comparative Statics in the Multi-Sector Equilibrium

- Use calibrated model to perform 4 exercises
  - $p_R/w \to 0$
  - 25% fall in MRTS between labor and robots *in all sectors*
  - 25% fall in MRTS between labor and robots *only in Automotive*
  - 25% fall in robot adjustment costs
- Compute GE prices and quantities, look at sectoral labor change

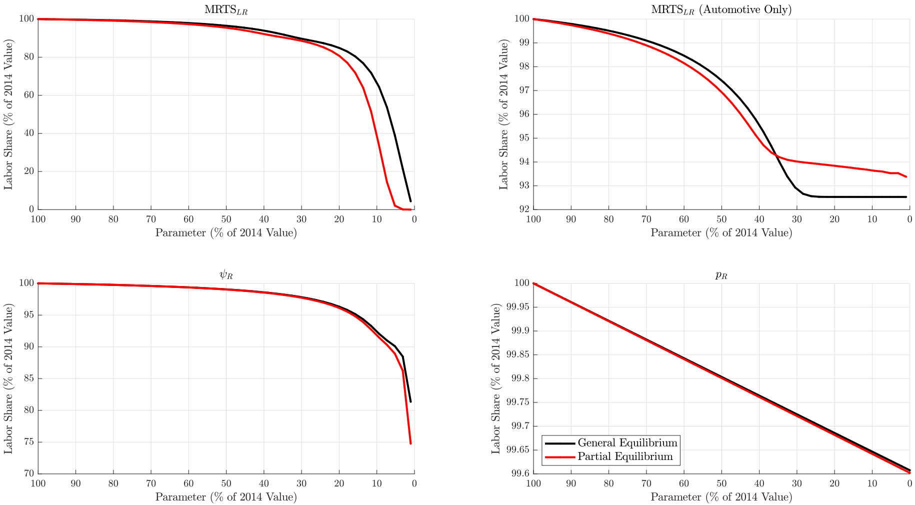
Sectoral (Production Line) Labor Change



Aggregate (Production Line) Labor Change



(Production Line) Labor Share Change



Comparative Statics Summary

Findings:

- negligible effect of p_R, both overall and compared to changes in Γ_s and ψ_R
  - low penetration in the data suggests high Γ_s and ψ_R, dampening price effects
  - lower Γ_s and/or $\psi_R \rightarrow$ more penetration $\rightarrow p_R$ has a larger impact
- Biggest threat from increased robot productivity and/or higher versatility
- In GE, wage cuts and reallocation safeguard labor, but labor share falls as much as in PE

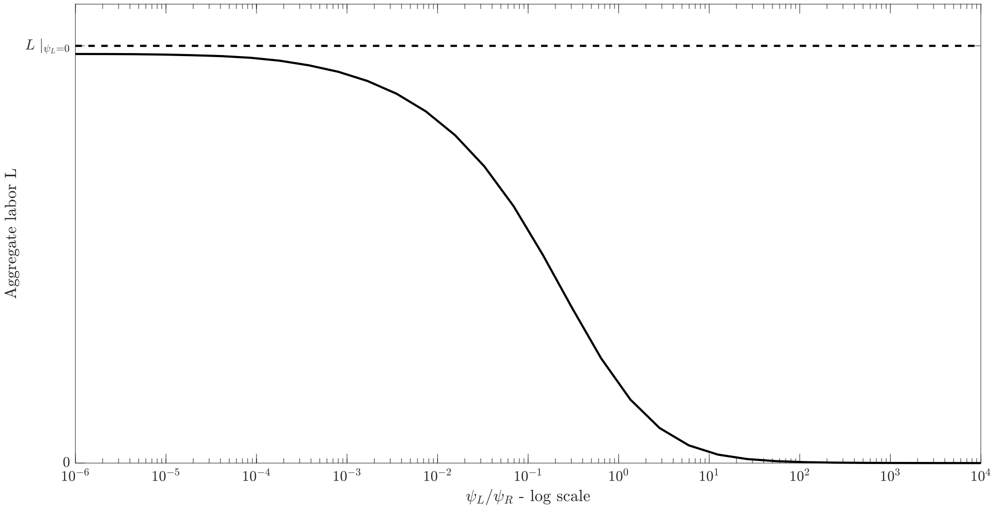
Beyond Perfectly Flexible Labor

- Adjusting labor is not frictionless
- Extension of Theoretical Analysis:
    - reduced form labor adjustment costs
    - partial equilibrium, i.e., fix wage w
- Firms choose utilization instantly, and hiring and investment intensity:

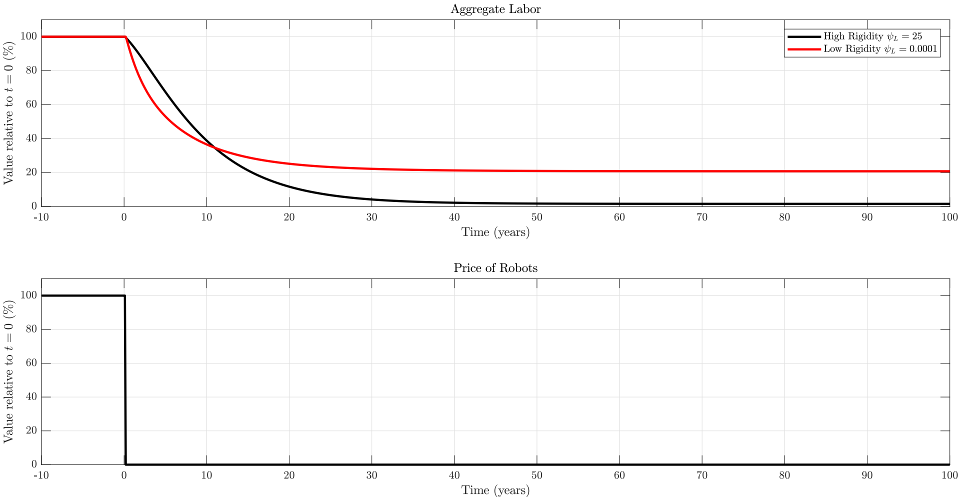
$$\Pi(R,L,z) = \max_{0\le u_L, u_R \le 1} \; pz\left(\Gamma u_L L + (1-\Gamma)\, u_R R\right)^{\theta} - m u_R R - wL$$

$$\rho V(R,L,z) = \max_{I_R, I_L} \Pi(R,L,z) - p_R I_R - \frac{\psi_R}{2} I_R^2 + (I_R - \delta R)\, V_R(R,L,z) + \\ - \frac{\psi_L}{2} I_L^2 + (I_L - sL)\, V_L(R,L,z) + \text{Ito Terms}$$

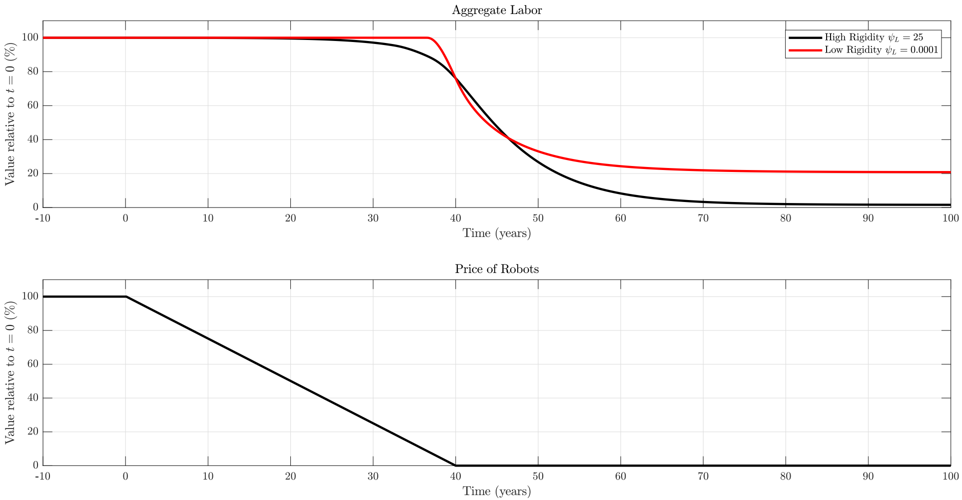
Effect of Labor Market Rigidities



Sudden Technology Shock - Transition



Gradual Technology Shock - Transition



Summary

- In steady state, labor rigidities unambiguously lead to more automation
- However, transitions are less straightforward
  - Sudden and large shocks $\rightarrow$ labor market rigidities smooth out the transition
  - Anticipated and gradual shocks $\rightarrow$ labor market rigidities induce firms to *anticipate* labor substitution, but automation occurs at a slower pace

Conclusions

- Theoretical Analysis:
  - With idiosyncratic shocks, adjustment costs on robots, flexible hiring and firing, then firms may still find it optimal to employ labor even when robots are cheaper on a productivity-adjusted basis
  - Labor is hired in bursts to cope with shocks
  - Our model is qualitatively consistent with recent findings from empirical literature
- Quantitative Analysis:
  - Reductions in the purchase price of robots have a small effect on employment
  - Major threat arises from innovations that make robots more productive, or reduce adjustment costs/specificity
- Extension with Rigid Labor:
  - More labor rigidity associated to lower employment in the steady state
  - Ambiguous role for labor flexibility along the transition to lower robot prices

THANK YOU!

Non-Convex Adjustment Costs

Back

- Use linear adjustment costs as follows (à la Bertola Bentolila, 1990):

$$\rho V(R,z) = \max_{I \in \mathbb{R}} \quad \Pi(R,z) - 1\{I>0\}(\psi_+ + p_R)I - 1\{I<0\}(-\psi_- + p_R)I +$$
$$+ (I - \delta R)V_R(R,z) + \text{Ito Terms}$$

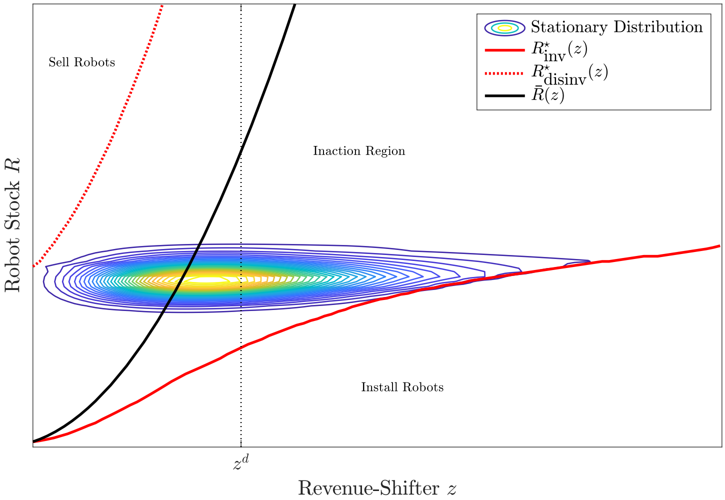
- This implies that, for each z, the firm will be inactive for $R \in [R^\star_{\text{inv}}(z), R^\star_{\text{disinv}}(z)]$, where

$$V_R\left(R^\star_{\text{inv}}(z), z\right) = p_R + \psi_+ \quad \text{and} \quad V_R\left(R^\star_{\text{disinv}}(z), z\right) = p_R - \psi_-,$$

  so that the stationary distribution has support within the inaction region.
- If ψ_+ is high enough, then partial automation occurs eventually analogously to convex cost case.
- Intuition carries over also to fixed costs of adjustment.

Robustness

Back



Calibration of Cox-Ingersoll-Ross Process

Back

We fit the following process:

$$\mathrm{d}z_t = -\theta_{z,s}\left(z_t - \underbrace{z^d}_{=1}\right)\mathrm{d}t + \sigma_{z,s}\sqrt{z_t}\,\mathrm{d}W_t$$

- Step 1: use Computstat Data (1950-2019) and build K_{ist} using perpetual inventory method with linear interpolation of investment
- Step 2: estimate TFP as residual from the following regression:

$$\log\left(\text{sales}_{ist}\right) = \gamma_i + f_{st} + \alpha_s \log\left(\text{emp}_{ist}\right) + \beta_s \log\left(K_{is,t-1}\right) + \varepsilon_{ist}$$

- Step 3: fit a firm specific Linear Trend on the estimated series to focus on idiosyncratic component of TFP
- Step 4: estimate parameters of CIR process by Maximum Likelihood, using a procedure adapted from Wei et alii (2016)

Calibration of ψ_R/w ▸ Back

We show that in the limit case discussed above,

$$\tilde{\Gamma}_s\left(\frac{\psi_R}{w}\right) = \left[1 + \frac{m}{w} + (\rho+\delta)\left(\delta\frac{\psi_R}{w}\left(\frac{R}{L}\right)_{s,2014}\xi_s + \left(\frac{p_R}{w}\right)_{2014}\right)\right]^{-1}$$

So, assuming at the true Γ_s the equilibrium is such that the limit case is approximately verified, then:

- Step 1: Guess initial value for $\frac{\psi_R}{w}$
- Step 2: Find equilibrium prices and wage in 2010 and 2014 setting $\Gamma_s = \tilde{\Gamma}_s$ and fixing the relative robot prices at their respective levels
- Step 3: Compute aggregate robot penetration in 2010 and 2014 and the deviation from the percentage change in the data
- Step 4: Update guess and go back to Step 2 until convergence

Calibration of Γ_s Back

The calibration of the sector-specific Γ_s follows that of ψ_R/w.

- Step 1: Guess initial value of Γ_s using $\tilde{\Gamma}_s$ evaluated at the calibrated ψ_R/w as starting point
- Step 2: Find equilibrium prices and wage that clear the markets in 2014 given Γ_s and the relative robot price p_R/w in 2014.
- Step 3: Compute deviation of sector specific $(R/L)_s$ from their targets
- Step 4: Update guesses Γ_s and go back to Step 2 until convergence

Constant-Across-Sectors Parameter Values

Back

The following parameters are common across all sectors:

Description	Parameter	Value	Source/Target
Relative robot price in 2010	$\left(\frac{p_R}{w}\right)_{2010}$	1.4348	Korus(2019) and OES
Relative robot price in 2014	$\left(\frac{p_R}{w}\right)_{2014}$	1.0209	Korus(2019) and OES
Relative flow robot cost	$\left(\frac{m}{w}\right)$	0	Energy costs captured by ψ_R
Robot depreciation	δ	$\log(1+1/12)$	IFR (2017)
Discount factor	ρ	$\log(1+0.04)$	4% annual interest rate
Adjustment cost parameter	ψ_R	1278.96	2010-14 change in aggr R/L

Sector-Specific Parameter Values

Back

The following parameters and targets are sector-specific:

Sector	R/L 2010	R/L 2014	ξ	θ	Γ	σ_z	θ_z
Automotive	88	117	0.065	0.35	0.52	0.13	0.77
Electronics	10	13	0.15	0.28	0.77	0.19	0.72
Food and Beverages	4.9	6.2	0.12	0.21	0.85	0.13	0.47
Wood and Furniture	0.022	0.14	0.028	0.41	0.89	0.13	0.63
Miscellaneous	2.4	14	0.04	0.32	0.85	0.18	0.84
Basic Metals	5.4	7.2	0.031	0.38	0.87	0.12	0.67
Industrial Machinery	1.8	2.4	0.078	0.33	0.88	0.14	0.71
Metal Products	6.2	8.3	0.07	0.35	0.84	0.12	0.91
Clay Glass and Minerals	0.28	0.68	0.024	0.33	0.89	0.13	0.7
Paper and Publishing	0.0085	0.11	0.047	0.28	0.89	0.1	0.62
Plastics, *et cetera*	8	9.9	0.27	0.18	0.78	0.61	0.89
Apparel and Textiles	0.0081	0.045	0.014	0.43	0.89	0.098	0.54
Shipbuilding and Aerospace	0.15	0.54	0.068	0.32	0.89	0.13	0.77