# Choosing Technologies: Benefits of Investing into the Fourth Industrial Revolution

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# Fourth Industrial Revolution: Automation of the Economy

- **Technology trend across technology fields** (Ménière et al. (2017))
  - Driven by the internet of things
  - Allowing to build systems of smart connected objects
  - Enables use of further technology e.g. cloud computing, AI

- **Large-scale automation of task groups and *intellectual* tasks**

# Fourth Industrial Revolution: Application Areas

- Enterprises

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- Infrastructure

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- Products / Home and personal use

# 4IR: Potential Benefits and Costs

- **Developing 4IR technology is an important opportunity for increased firm performance**
  - Highly flexible production (Bartel et al. (2007))
  - More customizable/ personalized products & services (Bartel et al. (2007))
  - Better informed decision making (Brynjolfsson et al. (2011))
  - Cost savings and less uncertainty (Bresnahan et al. (2002), Arvanitis (2005))

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- **Developing and incorporating the technology comes with many challenges**
  - Major changes in production processes (Sung (2018))
  - Need to acquire different competences/knowledge (McKinsey (2017))

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- **Developing and incorporating the technology comes with many challenges**
  - Major changes in production processes (Sung (2018))
  - Need to acquire different competences/knowledge (McKinsey (2017))
- **When deciding which technology type to develop firms have to compare expected long-run benefits**

# Our Research Question and (Planned) Approach

- **What are the long-run expected net benefits of developing 4IR?**

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- **Construct a dynamic structural model of firms' decisions to develop different technologies**
  - Differentiate between 4IR-related and non-4IR-related technology
  - Account for dynamic nature of technology development decisions
  - Allow productivity to develop endogenously
  - Expressions for expected long-run benefits
- **Estimate its parameters with a large panel data set (1993-2018)**

# Our Research Question and (Planned) Approach

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  - Account for dynamic nature of technology development decisions
  - Allow productivity to develop endogenously
  - Expressions for expected long-run benefits
- **Estimate its parameters with a large panel data set (1993-2018)**
- **Calculate long-run benefits of both 4IR and non-4IR technology**
- **Conduct counterfactual analyses, e.g. to assess the impact of 4IR subsidies**

# Main Contributions

- **Productivity effects of digital technologies** (Brynjolfsson et al. (2011), Bartel et al. (2007),Stiroh (2002),Bertschek et al. (2013),...)
  - ⇒ Investigate productivity effects of (different types of) 4IR technology
  - ⇒ Evolution of productivity effects over time
  - ⇒ Employ new patent classification as a measure for 4IR technology

# Main Contributions

- **Productivity effects of digital technologies** (Brynjolfsson et al. (2011), Bartel et al. (2007),Stiroh (2002),Bertschek et al. (2013),...)
  - ⇒ Investigate productivity effects of (different types of) 4IR technology
  - ⇒ Evolution of productivity effects over time
  - ⇒ Employ new patent classification as a measure for 4IR technology

- **Dynamic models of R&D choice** (Aw et al. (2011),Peters et al. (2017),...)
  - ⇒ Differentiate between R&D for different types of technology
  - ⇒ Calculate short- and long-run benefits and development costs

# Key Take-Aways

- Significant **positive productivity effects** of **4IR and non-4IR technology**
- **Productivity effects** of developing **4IR** technology is **higher**
- Evidence of **installation phase** arguments:
  - **No productivity effects** of 4IR in **early periods**,
  - but **strong effects** in **later period**

# Theoretical Model: Overview

- **Extension of R&D choice models** (Aw et al. (2011), Peters et al 2017, 2020)
  - Model links R&D/innovation $\longrightarrow$ productivity $\longrightarrow$ short-run firm profits $\longrightarrow$ long-run benefits
  - Extension allowing for R&D choice in different technology types
    - 4IR technology ($d_{it}$)
    - Non-4IR technology ($n_{it}$)

# Theoretical Model: Overview

- **Theoretical model consists of three parts**
  1) Consumer demand, short-term profits and price setting
  2) Productivity development
  3) Dynamic development decision and innovation cost

# Theoretical Model: Part 1 - Firm Profits

- **Revenues**

$$R_{it}(\omega_{it}) = \left(\frac{\eta_j}{1+\eta_j}\right)^{1+\eta_j} \Phi_{jt} C(\cdot)^{1+\eta_j} e^{-(1+\eta_j)\omega_{it}} \quad (1)$$

- $\omega_{it}$ combines production efficiency and demand shifter into revenue productivity
- Firm **profits**

$$\pi(\omega_{it}) = -\frac{1}{\eta_j} R_{it} \quad (2)$$

# Theoretical Model: Part 2 - Productivity Development

- Technology development decision affects firm's productivity
- Productivity $\omega_{it}$ evolves as an endogenous Markov process

$$\omega_{it+1} = g(\omega_{it}, d_{it}, n_{it}) + \xi_{it+1}, \ \ with\ \xi_{it+1} \sim f(0, \sigma_{\xi}^{2})$$
$$\omega_{it} = \alpha_1 \omega_{it\text{-}1} + \alpha_2 \omega_{it\text{-}1}^{2} + \alpha_3 \omega_{it\text{-}1}^{3} + \alpha_4 d_{it\text{-}1} + \alpha_5 n_{it\text{-}1} + \alpha_6 d_{it\text{-}1} \cdot n_{it\text{-}1} + \xi_{it} \tag{3}$$

# Theoretical Model: Part 3 - Dynamic Development Decision

- Technology development is costly
- **Development costs** unobserved
- We model them as a random draw from an exponential distribution

$$\begin{aligned} C_{it}^{d} &\sim exp(\gamma^{d}(K_{it}, d_{it-1})), \\ C_{it}^{n} &\sim exp(\gamma^{n}(K_{it}, n_{it-1})). \end{aligned} \tag{4}$$

- $\gamma^d, \gamma^n$: Technology development cost parameter for 4IR- and non-4IR innovation cost distributions

# Theoretical Model: Part 3 - Dynamic Development Decision

- The firm has **four choice possibilities** (and four expected future value functions):

$$V(s_{it}) = \pi(\omega_{it}) + \int_{C^d}\int_{C^n} \max_{d,n\in\{0,1\}} \begin{Bmatrix} \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}=0, n_{it}=0)]; \\ \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}=0, n_{it}=1)] - C^n_{it}; \\ \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}=1, n_{it}=0)] - C^d_{it}; \\ \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}=1, n_{it}=1)] - C^n_{it} - C^d_{it} \end{Bmatrix} dC^d dC^n$$

- with choice specific **expected future values** as

$$E[V(s_{it+1}|\omega_{it}, d_{it}, n_{it})] = \int_\omega V(s_{it+1}|\omega_{it}, d_{it}, n_{it}) dG\left(\omega_{it+1}|\omega_{it}, d_{it}, n_{it}\right) \qquad (5)$$

# Theoretical Model: Part 3 - Long-run Benefit of Developing 4IR Technology

- **Marginal benefit** of technology development investment is given by the difference in expected future value of the firm:
  - **Developing 4IR technology**

$$\Delta_d E_t[V(s_{it+1})] = \delta E_t[V(s_{it+1}|\omega_{it}, n_{it}; d_{it} = 1)] - \delta E_t[V(s_{it+1}|\omega_{it}, n_{it}; d_{it} = 0)] \quad (6)$$

  - **Developing non-4IR technology**

$$\Delta_n E_t[V(s_{it+1})] = \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}; n_{it} = 1)] - \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}; n_{it} = 0)] \quad (7)$$

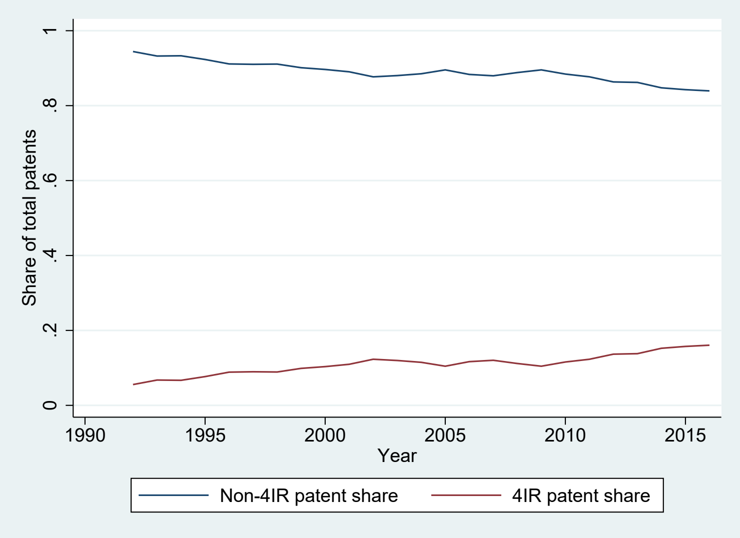
# Data

- **Mannheim Innovation Panel (MIP)**
  - Representative survey of German innovative firms
  - Period 1993-2018
  - Information on firm variables (employees, material, capital, revenues, industry classification )

- **Patent data**
  - PATSTAT - Worldwide patent database
  - Large number of patent characteristics (patent holder, patent family, citations, etc.)
  - Patent classification from EPO for belonging to 4IR 4IR Classification

- Combined we have 45,401 observations (16,580 firms) between 1993 and 2016 Summary statistics

# Increasing Share of 4IR Patents over Time



# Estimation

- We estimate all model parameters in two stages
- 1st stage
  - Estimate the revenue function to get all static parameters using NLLS

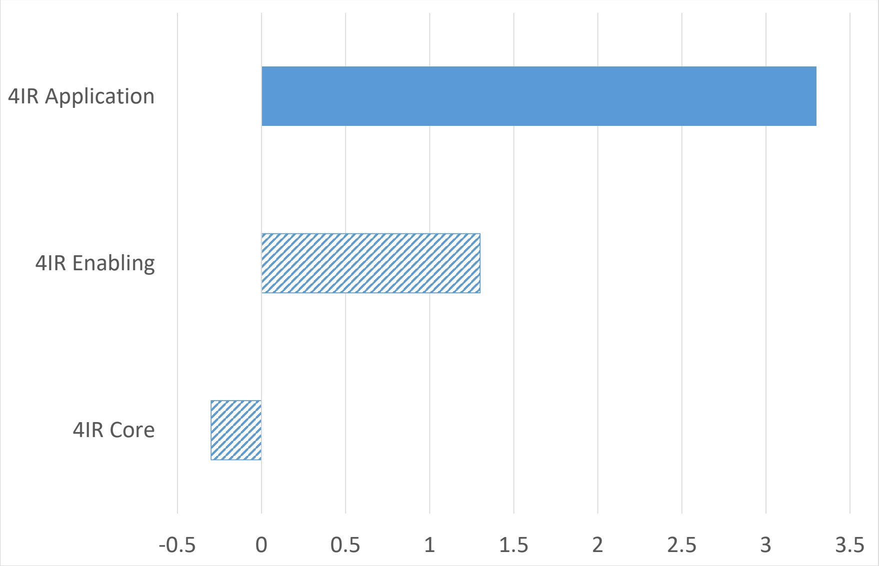
$$r_{it} = \lambda_{jt} + (1+\eta_j)(\beta_0 + \beta_k k_{it} + \sum_{z=1}^{Z} \beta_{a_z} A_{it}^{z} + \beta_e E_{it}$$
$$- (\alpha_1 \omega_{it\text{-}1} + \alpha_2 \omega_{it\text{-}1}^2 + \alpha_3 \omega_{it\text{-}1}^3 + \alpha_4 d_{it\text{-}1} + \alpha_5 n_{it\text{-}1} + \alpha_6 d_{it\text{-}1} \cdot n_{it\text{-}1}) + \epsilon_{it}$$

  - Calculate productivity ($\omega_{it}$) and profits for second stage
- 2nd stage
  - Estimating dynamic parameters (cost parameters, value function and expected value function) using nested fixed point

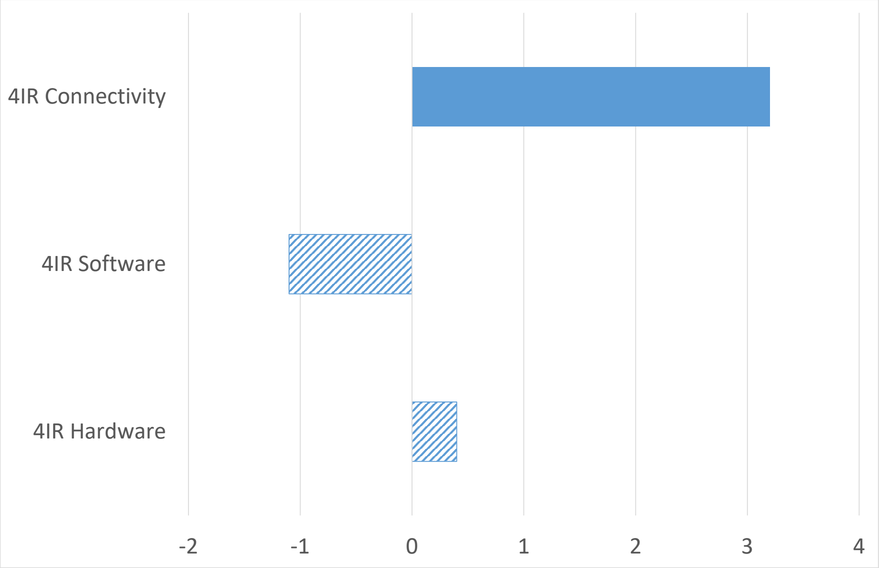
# Developing 4IR and Non-4IR Technologies Increases Productivity But ...

| | Digi and non-digi dummies | | | |
|---|---|---|---|---|
| Variables | Full | Early | Middle | Late |
| $\omega_{t-1}$ | 0.639*** | 0.679*** | 0.652*** | 0.672*** |
| | (0.0127) | (0.0230) | (0.0174) | (0.0159) |
| $\omega^2_{t-1}$ | 0.162*** | 0.152*** | 0.173*** | 0.150*** |
| | (0.00465) | (0.00890) | (0.00792) | (0.00604) |
| $\omega^3_{t-1}$ | -0.0296*** | -0.0318*** | -0.0361*** | -0.0296*** |
| | (0.000974) | (0.00202) | (0.00230) | (0.00145) |
| $4IR_{t-1}$ | 0.0828*** | 0.0258 | 0.0404 | 0.134*** |
| | (0.0192) | (0.0404) | (0.0348) | (0.0277) |
| Non-$4IR_{t-1}$ | 0.0675*** | 0.0574*** | 0.0662*** | 0.0711*** |
| | (0.00457) | (0.00956) | (0.00749) | (0.00711) |
| $4IR_{t-1} \cdot$ Non-$4IR_{t-1}$ | -0.0609*** | 0.0371 | -0.0379 | -0.113*** |
| | (0.0206) | (0.0460) | (0.0371) | (0.0296) |
| Capital | -0.0890*** | -0.0570*** | -0.105*** | -0.100*** |
| | (0.00180) | (0.00321) | (0.00318) | (0.00289) |
| Export | -0.0726*** | -0.0327*** | -0.0667*** | -0.104*** |
| | (0.00659) | (0.0126) | (0.0111) | (0.0106) |
| $A^2$ : 10 − 19 | -0.0133 | 0.000608 | 0.0262 | -0.0502** |
| | (0.0145) | (0.0324) | (0.0222) | (0.0249) |
| $A^3$ : 20 − 49 | -0.0603*** | -0.0474 | -0.0978*** | -0.0492** |
| | (0.0142) | (0.0302) | (0.0239) | (0.0234) |
| $A^4$ : 50+ | -0.146*** | -0.196*** | -0.170*** | -0.0898*** |
| | (0.0159) | (0.0300) | (0.0257) | (0.0278) |
| $N$ | 21,509 | 5,093 | 6,944 | 9,472 |

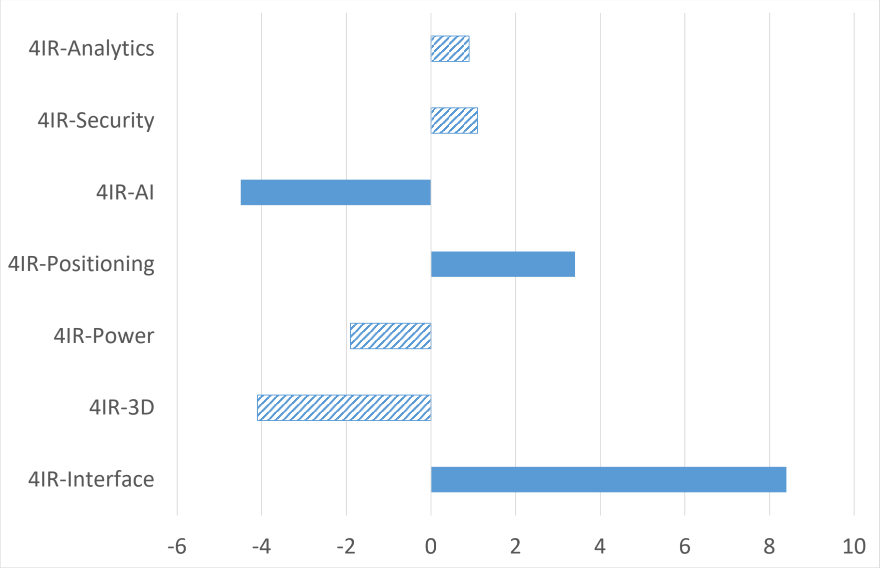
# Productivity Impact of Different Types of 4IR Technologies



# Productivity Impact of Core Technologies



# Productivity Impact of Enabling Technologies



# Conclusion and Outlook

- Constructed a structural model of firm's technology development choice
- Positive productivity effects of developing 4IR
- Early developers did not experience significant productivity effects
- Effect increases substantially over time
- Higher effect for 4IR technology than for non-4IR technology
- High productivity effects especially for 4IR applications (positioning, interface) and core technologies (connectivity)
- No average productivity returns yet to AI
- Outlook: Long-run benefits and policy simulations

Thanks for your attention!

# Appendix: Demand Elasticities

| Industry | Full sample $\eta$ | 1993-2000 $\eta$ | 2001-2008 $\eta$ | 2009-2016 $\eta$ |
|---|---|---|---|---|
| Food | -3.15*** | -3.08*** | -3.21*** | -3.15*** |
| Textiles | -3.64*** | -3.73*** | -3.78*** | -3.49*** |
| Paper/wood | -3.54*** | -3.48*** | -3.64*** | -3.51*** |
| Chemicals | -3.09*** | -3.04*** | -3.12*** | -3.11*** |
| Plastic | -3.69*** | -3.52*** | -3.87*** | -3.77*** |
| Minerals | -3.27*** | -3.25*** | -3.45*** | -3.16*** |
| Metal | -3.93*** | -3.95*** | -4.19*** | -3.75*** |
| Machinery | -3.99*** | -4.01*** | -4.08*** | -3.90*** |
| Electronics | -3.94*** | -3.86*** | -3.95*** | -3.99*** |
| Instruments | -3.56*** | -3.73*** | -3.76*** | -3.34*** |
| Vehicles | -4.37*** | -4.44*** | -4.42*** | -4.29*** |
| Misc. manuf. | -3.34*** | -3.41*** | -3.46*** | -3.23*** |
| *N* | 51645 | 16712 | 14215 | 20718 |

*Notes:* Significance at the * 5% level, ** 1% leve1, *** 0.1% level. Time and industry dummies variables are included in estimation but not reported.

# Appendix: Summary Statistics

| Variable | Model | Unit | mean | med | sd | min | max |
|---|---|---|---|---|---|---|---|
| Revenues | $R$ | mio € | 384.955 | 6.564 | 2585.008 | 0 | 82106.4 |
| Fixed capital | $K$ | mio € | 201.092 | 1.397 | 1710.461 | 0 | 61201.2 |
| Material cost | $M$ | mio € | 254.934 | 2.285 | 1882.106 | 0 | 69101.4 |
| Labor cost | | mio € | 56.916 | 1.96 | 375.290 | 0 | 13744.0 |
| Total variable cost | $C^M q$ | mio € | 311.851 | 4.645 | 2179.944 | 0 | 71090.0 |
| Firm age | | | | | | | |
| 0-9 | $A^1$ | 0/1 | .197 | 0 | .398 | 0 | 1 |
| 10-19 | $A^2$ | 0/1 | .277 | 0 | .447 | 0 | 1 |
| 20-49 | $A^3$ | 0/1 | .288 | 0 | .453 | 0 | 1 |
| 50+ | $A^4$ | 0/1 | .219 | 0 | .414 | 0 | 1 |
| Exporter | $E$ | 0/1 | 0.548 | 1 | 0.498 | 0 | 1 |
| Non-digital tech | $n$ | 0/1 | 0.074 | 0 | 0.261 | 0 | 1 |
| Digital tech | $d$ | 0/1 | 0.024 | 0 | 0.153 | 0 | 1 |

*Notes:* Number of observations: 45589. Sample period: 1993-2016. For ease of representation, all monetary variables are in million euro, for estimation we use their log values.

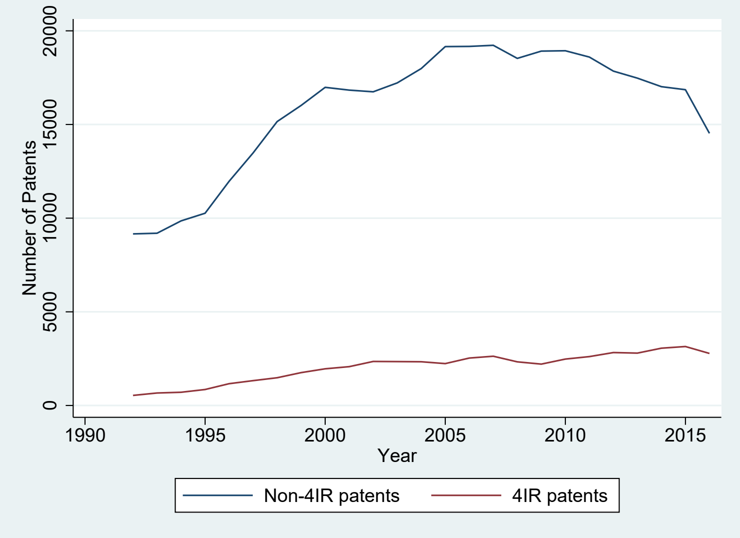
back

# 4IR Patent classification

- Developed by the European Patent Office in 2017
- Patent examiners from all technology fields identified 320 CPC fields they relate to building blocks of 4IR
- Three building blocks

| Technologies | Description | Examples |
|---|---|---|
| Core technologies | Basic technologies to build 4IR technology on | sensors, cloud storage, adaptive databases |
| Enabling technologies | Build on core technologies and allow a variety of application domains | big data diagnostics, virtual reality, position determination sys. |
| Application domains | Applications using core- and enabling technologies | intelligent robotics, smart home sys., wearables |

# Development of 4IR and Non-4IR Patents over Time




back

# Data: Patents per Industry

| Industry | Non-4IR Patents | 4IR Patents | % 4IR Patents | Total Patents |
|---|---|---|---|---|
| Food | 474 | 9 | .0186 | 483 |
| Textiles | 1,117 | 89 | .0738 | 1,206 |
| Paper/Wood | 2,564 | 600 | .1896 | 3,164 |
| Chemicals | 52,432 | 1,203 | .0224 | 53,635 |
| Plastic | 4,616 | 130 | .0274 | 4,746 |
| Minerals | 2,068 | 67 | .0314 | 2,135 |
| Metal | 5,156 | 214 | .0399 | 5,370 |
| Machinery | 38,392 | 3,318 | .0795 | 41,710 |
| Electronics | 46,763 | 14,407 | .2355 | 61,170 |
| Instruments | 11,421 | 2,936 | .2045 | 14,357 |
| Vehicles | 26,518 | 7,658 | .2241 | 34,176 |
| Misc. manuf. | 890 | 98 | .0992 | 988 |
| Total/Average | 200,852 | 34,475 | .1465 | 235,327 |

# Appendix: Theoretical Model: Part 1 - Consumer Demand

- Assume monopolistic competition (Dixit and Stigliz (1977))
  - Allows for differentiated goods
  - Allows for short-term profits
  - No strategic interactions
- **Demand** for each firm *i*'s

$$q_{it} = \left(\frac{p_{it}}{P_{jt}}\right)^{\eta_j} \frac{I_{jt}}{P_{jt}} e^{\phi_{it}} = \Phi_{jt} p_{it}^{\eta_j} e^{\phi_{it}}, \quad (8)$$

  - $P_{jt}$ : Industry *j*'s price index
  - $I_{jt}$ : Market size
  - $\eta_j$ : Demand Elasticity
  - $\phi_{it}$ : Demand shifter

# Appendix: Theoretical Model: Part 1 - Price Setting

- **Marginal costs**

$$C_{it}^{M} = \frac{C\left(K_{it}, W_{it}, A_{it}, E_{it}\right)}{e^{\psi_{it}}} \tag{9}$$

  - $K_{it}$ : Capital stock
  - $W_{it}$: Input market prices
  - $A_{it}$ : Firm age
  - $E_{it}$ : Export status
  - $\psi_{it}$ : Production efficiency

# Appendix: Theoretical Model: Part 1 - Price Setting

- **Marginal costs**

$$C_{it}^{M} = \frac{C\left(K_{it}, W_{it}, A_{it}, E_{it}\right)}{e^{\psi_{it}}} \tag{10}$$

  - $K_{it}$ : Capital stock
  - $W_{it}$: Input market prices
  - $A_{it}$ : Firm age
  - $E_{it}$ : Export status
  - $\psi_{it}$ : Production efficiency

- The **price setting rule** given by profit maximization

$$p_{it} = \frac{\eta_j}{1 + \eta_j} C_{it}^{M} \tag{11}$$

# Appendix: Theoretical Model: Part 1 - Firm Profits

- **Revenues**

$$R_{it} = p_{it} q_{it} = \left( \frac{\eta_j}{1+\eta_j} \right)^{1+\eta_j} \Phi_{jt} C\left(\cdot\right)^{1+\eta_j} e^{-(1+\eta_j)\omega_{it}} \tag{12}$$

- Combine production efficiency and demand shifter into revenue productivity $\omega_{it}$

# Appendix: Theoretical Model: Part 1 - Firm Profits

- **Revenues**

$$R_{it} = p_{it} q_{it} = \left(\frac{\eta_j}{1+\eta_j}\right)^{1+\eta_j} \Phi_{jt} C\left(\cdot\right)^{1+\eta_j} e^{-(1+\eta_j)\omega_{it}} \tag{13}$$

- Combine production efficiency and demand shifter into revenue productivity $\omega_{it}$
- Firm **profits**

$$\pi_{it} = \pi(\omega_{it}) = R_{it} - C^M_{it} q_{it} = -\frac{1}{\eta_j} R_{it} \tag{14}$$

# Appendix: Theoretical Model: Part 2 - Productivity Development

- Technology development decision affects firm's productivity
- Productivity $\omega_{it}$ evolves as an endogenous Markov process

$$\omega_{it+1} = g(\omega_{it}, d_{it}, n_{it}) + \xi_{it+1}, \ \ with \ \xi_{it+1} \sim f(0, \sigma_{\xi}^2) \tag{15}$$

# Appendix: Theoretical Model: Part 3 - Dynamic Development Decision

- Technology development is costly
- **Development costs** unobserved
- We model them as a random draw from an exponential distribution

$$C_{it}^{d} \sim exp(\gamma^{d}(K_{it}, d_{it-1})), \\ C_{it}^{n} \sim exp(\gamma^{n}(K_{it}, n_{it-1})). \tag{16}$$

- $\gamma^d, \gamma^n$: Technology development cost parameter for 4IR- and non-4IR innovation cost distributions

# Appendix: Theoretical Model: Part 3 - Dynamic Development Decision

- Firms choose to develop $d$ or $n$ to maximize their discounted future value
- Their **value function** is

$$V(s_{it}) = \pi(\omega_{it}) + \delta E[V(s_{it+1}|\omega_{it}, d_{it}, n_{it})] - E[C^d_{it} \cdot d_{it}] - E[C^n_{it} \cdot n_{it}], \qquad (17)$$

with $s_{it} = (\omega_{it}, K_{it}, d_{it-1}, n_{it-1})$

and $\delta$ as a discount factor

# Appendix: Theoretical Model: Part 3 - Dynamic Development Decision

- The firm has **four choice possibilities** (and four expected future value functions):

$$V(s_{it}) = \pi(\omega_{it}) + \int_{C^d}\int_{C^n} \max_{d,n\in\{0,1\}} \left\{ \begin{array}{l} \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}=0, n_{it}=0)]; \\ \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}=0, n_{it}=1)] - C^n_{it}; \\ \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}=1, n_{it}=0)] - C^d_{it}; \\ \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}=1, n_{it}=1)] - C^n_{it} - C^d_{it} \end{array} \right\} dC^d dC^n$$

- with choice specific **expected future values** as

$$E[V(s_{it+1}|\omega_{it}, d_{it}, n_{it})] = \int_{\omega} V(s_{it+1}|\omega_{it}, d_{it}, n_{it}) dG\left(\omega_{it+1}|\omega_{it}, d_{it}, n_{it}\right) \qquad (18)$$

# Appendix: Theoretical Model: Part 3 - Benefit of Developing 4IR Technology

- **Marginal benefit** of technology development investment is given by the difference in expected future value of the firm:
  - Developing 4IR technology

$$\Delta_d E_t[V(s_{it+1})] = \delta E_t[V(s_{it+1}|\omega_{it}, n_{it}; d_{it} = 1)] - \delta E_t[V(s_{it+1}|\omega_{it}, n_{it}; d_{it} = 0)] \quad (19)$$

  - Developing non-4IR technology

$$\Delta_n E_t[V(s_{it+1})] = \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}; n_{it} = 1)] - \delta E_t[V(s_{it+1}|\omega_{it}, d_{it}; n_{it} = 0)] \quad (20)$$

# Appendix: Empirical Model: Overview

- We estimate all model parameters in two stages
- 1st stage
  - Estimate demand elasticity $\eta_j$
  - Estimate the revenue function to get all static parameters
    - Deal with simultaneity issue
    - Calculate productivity ($\omega_{it}$)
- 2nd stage
  - Estimating dynamic parameters (cost parameters, value function and expected value function)

# Appendix: Empirical Model: Stage 1 - Demand Elasticities

- Using profit equation 14

$$\pi_{it} = \pi(\omega_{it}) = -\frac{1}{\eta_j} R_{it} \Leftrightarrow \frac{C_{it}^M q_{it}}{R_{it}} = 1 + \frac{1}{\eta_j} \tag{21}$$

- Regress total variable cost - revenue ration on industry-specific constants
- Back out industry demand elasticity $\eta_j$ Results

# Appendix: Empirical Model: Stage 1 - Static Parameters

- Assume Cobb-Douglas type functional form of cost function
  - Assume input prices $W$ do not differ between firms (so $W_{it} = W_t$)

$$C(K_{it}, W_{it}, A_{it}, E_{it}) = K_{it}^{\beta_k} W_t^{\beta_w} e^{\beta_0 + \sum_{z=1}^{Z} \beta_{a_z} A_{it}^z + \beta_e E_{it}} \quad (22)$$

# Appendix: Empirical Model: Stage 1 - Static Parameters

- Assume Cobb-Douglas type functional form of cost function
  - Assume input prices $W$ do not differ between firms (so $W_{it} = W_t$)

$$C(K_{it}, W_{it}, A_{it}, E_{it}) = K_{it}^{\beta_k} W_t^{\beta_w} e^{\beta_0 + \sum_{z=1}^{Z} \beta_{a_z} A_{it}^z + \beta_e E_{it}} \tag{23}$$

- Inserting (23) into the revenue equation 13 and taking logs gives

$$r_{it} = \lambda_{jt} + (1 + \eta_j)(\beta_0 + \beta_k k_{it} + \sum_{z=1}^{Z} \beta_{a_z} A_{it}^z + \beta_e E_{it} - \omega_{it}) + \epsilon_{it} \tag{24}$$

  - $\lambda_{jt}$ includes all factors constant over firms in each industry
  - $\epsilon_{it}$ is an i.i.d, zero mean error term

# Appendix: Empirical Model: Stage 1 - Static Parameters

- Problem: Productivity $\omega_{it}$ is unobserved (simultaneity bias)
- Control function approach á la OP 1996, LP 2003 and ACF 2015
  $\Rightarrow$ Define $\omega_{it}$ as a function of observables

# Appendix: Empirical Model: Stage 1 - Static Parameters

- Problem: Productivity $\omega_{it}$ is unobserved (simultaneity bias)
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  $\Rightarrow$ Define $\omega_{it}$ as a function of observables
- We use model structure to get material demand equation

$$m_{it} = \beta_{jt} + (1+\eta)\beta_k k_{it} + (1+\eta)\sum_{z=1}^{Z}\beta_{a_z}A_{it}^{z} + (1+\eta)\beta_e E_{it} - (1+\eta)\omega_{it}$$

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$$\Leftrightarrow \omega_{it} = \left(\frac{1}{1+\eta_j}\right)\beta_{jt} + \beta_k k_{it} + \sum_{z=1}^{Z}\beta_{a_z}A_{it}^{z} + \beta_e E_{it} - \left(\frac{1}{1+\eta_j}\right)m_{it}$$

# Appendix: Empirical Model: Stage 1 - Static Parameters

- Assume functional form of productivity development process

$$\omega_{it} = \alpha_0 + \alpha_1 \omega_{it-1} + \alpha_2 \omega_{it-1}^2 + \alpha_3 \omega_{it-1}^3 + \alpha_4 d_{it-1} + \alpha_5 n_{it-1} + \alpha_6 d_{it-1} n_{it-1} + \xi_{it} \quad (25)$$

# Appendix: Empirical Model: Stage 1 - Static Parameters

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- Include inverse of the material demand equation in productivity evolution process
- Include both in revenue equation 24 to get final estimation equation

# Appendix: Empirical Model: Stage 1 - Static Parameters

- Assume functional form of productivity development process

$$\omega_{it} = \alpha_0 + \alpha_1\omega_{it-1} + \alpha_2\omega_{it-1}^2 + \alpha_3\omega_{it-1}^3 + \alpha_4 d_{it-1} + \alpha_5 n_{it-1} + \alpha_6 d_{it-1} n_{it-1} + \xi_{it} \quad (27)$$

- Include inverse of the material demand equation in productivity evolution process
- Include both in revenue equation 24 to get final estimation equation

$$\begin{aligned} r_{it} = \lambda_0 + \lambda_{jt} + (1+\eta_j)\beta_k k_{it} + (1+\eta_j)\textstyle\sum_{z=1}^{Z} \beta_{a_z} A_{it}^z + (1+\eta_j)\beta_e E_{it} \\ - \quad \alpha_1 \; [\beta_{jt-1} + (1+\eta_j)\beta_k k_{it-1} + (1+\eta_j)\textstyle\sum_{z=1}^{Z} \beta_{a_z} A_{it-1}^z + (1+\eta_j)\beta_e E_{it-1} - m_{it-1}] \\ - \frac{\alpha_2}{1+\eta_j} [\beta_{jt-1} + (1+\eta_j)\beta_k k_{it-1} + (1+\eta_j)\textstyle\sum_{z=1}^{Z} \beta_{a_z} A_{it-1}^z + (1+\eta_j)\beta_e E_{it-1} - m_{it-1}]^2 \\ - \frac{\alpha_3}{(1+\eta_j)^2} [\beta_{jt-1} + (1+\eta_j)\beta_k k_{it-1} + (1+\eta_j)\textstyle\sum_{z=1}^{Z} \beta_{a_z} A_{it-1}^z + (1+\eta_j)\beta_e E_{it-1} - m_{it-1}]^3 \\ - (1+\eta_j)[\alpha_4 d_{it-1} + \alpha_5 n_{it-1} + \alpha_6 d_{it-1} n_{it-1}] - (1+\eta_j)\xi_{it} + \epsilon_{it} \end{aligned} \quad (28)$$

- Estimate with NLLS

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