Skill-Replacing Process Innovation and the Labour Market: Theory and Evidence

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Introduction

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- Product innovation vs. process innovation

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- I focus on the labour market consequences of these two types of innovations
  - Hypothesis
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  - product innovation $\longrightarrow$ skill-complementing
  - process innovation $\longrightarrow$ skill-replacing
- Examples
  1. Standardization: assembly lines and interchangeable parts
  2. Autor (2015): environmental control

Kiva robots at an Amazon Warehouse

What I do

1. Estimate the relationship between the ratio of product to process innovation and the income share of low-skilled workers at the industry level.
   - Instrumental variables
2. Develop a model that captures the essence of the empirical finding.
3. Calibrate the model to two largest industries in UK, in 2014 and 2018
   - "Manufacturing" and "Wholesale and retail trade"

Main results

1. Empirical: more product innovation, relative to process innovation have a negative impact on the income share of low-skilled workers.
2. Theoretical: a GE model with innovations affect both the rate of growth and the income distribution.
3. Quantitative: In the UK, between 2014 and 2018
   - product innovation becomes less expensive to develop
   - new products become increasingly “non-routine” and thereby more skill demanding
   - the cost of process innovation has increased on average, and becomes more diverse

Literature review

- Labour saving technological change
  - Autor and Dorn (2013), Frey and Osborne (2017), Acemoglu and Restrepo (2018), Hemous and Olsen (2022)
- Innovation behaviour of incumbent firms
  - Bartelsman and Doms (2000), Foster, Haltiwanger, and Krizan (2001), Bresnahan, Brynjolfsson, and Hitt (2002), Bartelsman, Scarpetta, and Schivardi (2005), Barth et al. (2017), Akcigit and Kerr (2018)
  - Acemoglu, Gancia, and Zilibotti (2012)
- Empirical
  - Katz and Murphy (1992), Autor, Katz, and Krueger (1998), Krusell et al. (2000)
  - Caroli and Van Reenen (2001)
- Product vs. process
  - Dhingra (2013), Flach and Irlacher (2018)

Baseline specification

$$\frac{w_{L,i,c,t}L_{i,c,t}}{w_{L,i,c,t}L_{i,c,t} + w_{H,i,c,t}H_{i,c,t}} = \beta_0 + \beta_1 \frac{PD_{i,c,t-1}}{PC_{i,c,t-1}} + YEAR + COUNTRY + IND + \epsilon_{i,c,t}, \qquad (1)$$

- Identification
  1. lagged labour market data
  2. relative levels of technology
     - β_1 is expected to be negative
  3. reverse causality

Instrumental variables

- Product innovation is more resource intensive
  - Evidence: Granja and Moreira (2022), Friedrich and Zator (2023), Hellmann and Puri (2000), Fracassi, Previtero, and Sheen (2022)
  - Instrument: financial dependence - Rajan and Zingales (1998)

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  - Instrument: financial dependence - Rajan and Zingales (1998)
- Economy of scale vs. "Cannibalization"
  - Evidence: Dhingra (2013), Flach and Irlacher (2018)
  - Instrument: (1) average firm size and (2) enterprise group

Data I: Structure of Earnings Survey (SES)

- Available: 2002, 2006, 2010, 2014, 2018
- Year-Country-Industry
  - 14 single digit industries:
  - D - Manufacturing; F - Construction; J - Financial Intermediation; etc.
- Number of employees
- Annual income: Earnings + Bonuses
- Education level
  - high-skilled $\rightarrow$ ISCED 1997 level 5 and 6: college and above
  - low-skilled $\rightarrow$ ISCED 1997 level 3 and 4: high school and post-secondary non-tertiary educated

Data II: Community Innovation Survey (CIS)

- Available: 2000, 2004, 2006, 2008, 2010, 2012, 2014, 2016, 2018
- Year-Country-Industry
- PD: the number of firm reports *at least one* successful product innovation
- PC: the number of firm reports *at least one* successful process innovation
  - New-to-the-firm PD vs. new-to-the-market PD

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  - New-to-the-firm PD vs. new-to-the-market PD
- Unbalanced Panel
- Obs #1: Country A, Industry 1, 2002 wages, labour supplies, and 2000 innovations
- 35 countries, 14 industries, 5 years

Glossary:Product innovation

Translate

A **product innovation** is the introduction of a good or service that is new or significantly improved with respect to its characteristics or intended uses. This includes significant improvements in technical specifications, components and materials, incorporated software, user friendliness or other functional characteristics.

Product innovations can utilise new knowledge or technologies, or can be based on new uses or combinations of existing knowledge or technologies. The term 'product' is used to cover both goods and services. Product innovations include both the introduction of new goods and services and significant improvements in the functional or user characteristics of existing goods and services.

Glossary:Process innovation

Translate

A **process innovation** is the implementation of a new or significantly improved production or delivery method. This includes significant changes in techniques, equipment and/or software.

Process innovations can be intended to decrease unit costs of production or delivery, to increase quality, or to produce or deliver new or significantly improved products.

Process innovations include new or significantly improved methods for the creation and provision of services. They can involve significant changes in the equipment and software used in services-oriented firms or in the procedures or techniques that are employed to deliver services. Examples are the introduction of GPS tracking devices for transport services, the implementation of a new reservation system in a travel agency, and the development of new techniques for managing projects in a consultancy firm.

Process innovations also cover new or significantly improved techniques, equipment and software in ancillary support activities, such as purchasing, accounting, computing and maintenance. The implementation of new or significantly improved information and communication technology (ICT) is a process innovation if it is intended to improve the efficiency and/or quality of an ancillary support activity.

Main empirical results

	Dependent variable: $\frac{w_L L}{w_L L + w_H H}$							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$(PD/PC)_{t-1}$	-0.0441***				-0.0426***		-0.0441	
	(0.0160)				(0.0159)		(0.0243)	
$(PDM/PC)_{t-1}$		-0.0587***				-0.0566***		-0.0587*
		(0.0209)				(0.0210)		(0.0248)
$(ORG/PC)_{t-1}$			-0.0135					
			(0.0089)					
$(ORG/PD)_{t-1}$				-0.0005				
				(0.0070)				
$\log(Total)_{t-1}$					0.0138	0.0080		
					(0.0098)	(0.0107)		
YEAR	Y	Y	Y	Y	Y	Y	Y	Y
COUNTRY	Y	Y	Y	Y	Y	Y	Y	Y
INDUSTRY	Y	Y	Y	Y	Y	Y	Y	Y
Constant	0.5928***	0.5814***	0.5718***	0.5493***	0.4930***	0.5238***	0.5928***	0.5814***
	(0.0166)	(0.0120)	(0.0136)	(0.0123)	(0.0725)	(0.0786)	(0.0206)	(0.0087)
Observations	413	388	419	413	410	385	413	388
Adjusted R^2	0.789	0.809	0.792	0.788	0.792	0.811	0.788	0.808

Robust standard errors in parentheses, the last two columns are three-way clustered: year-country-industry.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Robustness checks: Time varying trends

	Dependent variable: $\frac{w_L L}{w_L L + w_H H}$			
	(1)	(2)	(3)	(4)
$(PD/PC)_{t-1}$	-0.0590***		-0.0357*	
	(0.0185)		(0.0211)	
$(PDM/PC)_{t-1}$		-0.0828***		-0.0560**
		(0.0264)		(0.0278)
YEAR	-	-	-	-
COUNTRY	-	-	-	-
INDUSTRY	-	-	-	-
YEAR × *COUNTRY*	Y	Y	Y	Y
YEAR × *INDUSTRY*			Y	Y
Constant	0.6078***	0.5947***	0.5836***	0.5792***
	(0.0190)	(0.0147)	(0.0215)	(0.0155)
Observations	410	385	405	382
Adjusted R^2	0.788	0.811	0.791	0.815

Robust standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Instrumental variable results

	Dependent variable: $\frac{w_L L}{w_L L + w_H H}$				
	(1)	(2)	(3)	(4)	(5)
$(PD/PC)_{t-1}$	-1.2275***	-0.8862*	-0.9287**	-0.4523**	-0.3839***
	(0.2956)	(0.4795)	(0.5445)	(0.2100)	(0.1426)
$\log(Total)_{t-1}$	0.1242***	0.0982***	0.1014***	0.0684***	0.0610***
	(0.0202)	(0.0291)	(0.0256)	(0.0117)	(0.0100)
YEAR	Y	Y	Y	Y	Y
COUNTRY	Y	Y	Y	Y	Y
Instrument(s)	FD_{t-2}		FD_{t-2}	$\log(AE_{t-1})$	$\log(AT_{t-1})$
		FD_{t-3}	FD_{t-3}	GP_{t-1}	GP_{t-1}
Constant	1.4361***	1.1067	1.1476*	0.8257***	0.7942***
	(0.4472)	(0.6735)	(0.6549)	(0.2087)	(0.1554)
Observations	398	398	398	313	309
K-P rk Wald F-stats	10.005	2.278	10.294	13.716	11.070
overid p-val	NA	NA	0.4978	0.2264	0.1014
Adjusted R^2	-3.178	-1.245	-1.446	0.311	0.424

Two-way clustered standard errors in parentheses (i.e., year-country), except for Column (1), which is clustered by country only.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Summary

- A negative correlation between the product to process innovation ratio and the income share of the low-skilled
- Impacts:
  - product innovation ⟶ skill-complementing
  - process innovation ⟶ skill-replacing

Model overview

- Endogenous growth model with expanding varieties (a la Romer 1990)
- Product innovation → new intermediate goods → "non-routine" (w/ prob θ)
  - requires high-skilled workers
- Process innovation: "non-routine" → "routine"
  - high-skilled workers or low-skilled workers
- Two extensions

Environment

- Time is discrete
- High-skilled and Low-skilled, H and L
- Intermediate goods, two modes of production: routine and non-routine
  - Non-routine: H, with productivity $\mu(> 1)$
  - Routine: H or L, with productivity 1
- A single final good: consumption and/or investment
- Product innovation: new intermediate goods
- Process innovation: non-routine $\Longrightarrow$ routine

Final good producers

- Production function for the final good

$$Y_t = N_t^{\frac{2\alpha-1}{\alpha}} \left[\sum_{j \in N_{L,t}} x_{L,j,t}^{\alpha} + \sum_{j \in N_{H,t}} x_{H,j,t}^{\alpha} \right]^{\frac{1}{\alpha}}, \alpha \in \left(\frac{1}{2}, 1 \right) \tag{2}$$

- Final good producers choose intermediate goods to minimize costs and earn zero profits

$$x_{L,j,t} = N_t^{\frac{2\alpha-1}{1-\alpha}} \left(\frac{1}{p_{L,j,t}} \right)^{\frac{1}{1-\alpha}} Y_t, \text{ and} \tag{3}$$

$$x_{H,j,t} = N_t^{\frac{2\alpha-1}{1-\alpha}} \left(\frac{1}{p_{H,j,t}} \right)^{\frac{1}{1-\alpha}} Y_t \tag{4}$$

Intermediate producers

- Intermediate producers competes for workers
- Wages are determined competitively
- Intermediate producers choose prices to maximize profits

$$p_{L,j,t} = \frac{w_{L,t}}{\alpha}, \text{ and } p_{H,j,t} = \frac{w_{H,t}}{\alpha\mu} \tag{5}$$

Innovations

- New intermediate goods arise as a result of **product innovation**
- Fixed cost of product innovation: $1/\eta$
  - with probability $\theta(> 1/2)$ the new intermediate good is non-routine
- Non-routine producers can engage in **process innovation**
  - $\rho_{j,t} \sim U(\bar{\rho} + \lambda, \underline{\rho} + \lambda)$
- The cost of innovation is denoted by the final good
  - Extension 1

Value functions

$$V_{L,t} = \pi_{L,t} + \frac{1}{1+r_t} V_{L,t+1}, \tag{6}$$

and

$$V_{H,t} = \pi_{H,t} + \frac{1}{1+r_t} \left[\gamma_t [V_{L,t+1} - E(\tilde{\rho}_{j,t} | \tilde{\rho}_{j,t} \leq \rho_t)] + (1-\gamma_t) V_{H,t+1} \right] \tag{7}$$

Optimal process innovation behavior

$$\gamma_t = Pr\left\{V_{H,t} \leq V_{L,t} - \tilde{\rho}_{j,t}\right\} = \frac{V_{L,t} - V_{H,t} - \underline{\rho} - \lambda}{\bar{\rho} - \underline{\rho}} \tag{8}$$

Flow of intermediate producers

$$\Delta N_{H,t} = \theta g_t N_t - \gamma_t N_{H,t}, \text{ and} \tag{9}$$

$$\Delta N_{L,t} = (1-\theta) g_t N_t + \gamma_t N_{H,t} \tag{10}$$

Euler equation and market clearing

$$\frac{c_{t+1}}{c_t} = \beta(1 + r_t), \tag{11}$$

and

$$C_t + I_t = Y_t \tag{12}$$

Labour market equilibrium

- "Complete-sorting"

$$L = x_{L,t} N_{L,t}, \text{ and } \mu H = x_{H,t} N_{H,t} \tag{13}$$

- Labour market clearing

$$x_{L,t} = \frac{L}{N_{L,t}}, \text{ and} \tag{14}$$

$$x_{H,t} = \frac{\mu H}{N_{H,t}} \tag{15}$$

- Final good production function

$$Y_t = \left[\chi_{L,t}^{1-\alpha} L^{\alpha} + (1 - \chi_{L,t})^{1-\alpha} (\mu H)^{\alpha} \right]^{1/\alpha} N_t, \tag{16}$$

where $\chi_{L,t} \equiv N_{L,t}/N_t$.

Skill premium

$$\frac{w_{H,t}}{w_{L,t}} = \mu^{\alpha} \left(\frac{1 - \chi_{L,t}}{\chi_{L,t}} \bigg/ \frac{H}{L} \right)^{1-\alpha}, \mu > 1, \text{ and } \alpha \in \left(\frac{1}{2}, 1 \right). \tag{17}$$

General Equilibrium

- Final good producers choose intermediate goods to minimize cost and earn zero profits (Equations 3 and 4)
- Intermediate goods producers set prices and hire workers to maximize profits (Equation 5)
- Non-routine intermediate producers choose whether to engage in process innovation optimally (Equation 8)
- Workers allocate themselves to the labour market which offers the highest wages for their skills
- Workers choose a consumption plan to maximize their utilities (Equation 11)
- Product innovators breaks even (i.e., free entry)

$$V_t = \theta V_{H,t} + (1 - \theta) V_{L,t} = \frac{1}{\eta} \tag{18}$$

- The goods markets, the labour markets, and the asset market all clear.

Balanced Growth Equilibrium (BGP)

There exists a balanced growth path (BGP) equilibrium, in which the output, the consumption, the wages for high-skilled and low-skilled workers, and in particular, both the measure of non-routine and routine intermediate producers grow at the same constant rate g^* (I use asterisk to denote BGP variables).

- Note that the share of routine intermediate producers, χ_L^*, and the skill premium, w_H^*/w_L^*, do not change over time on the BGP.

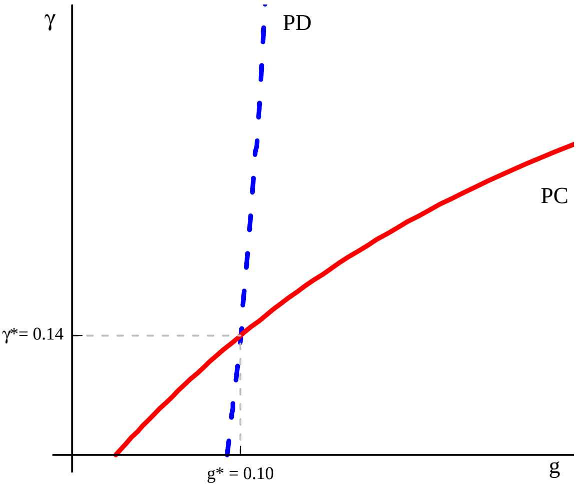
BGP Equilibrium Equations

- The BGP equilibrium can be solved for the rate of product innovation (g^*) and the rate of process innovation (γ^*)

$$\gamma^* = \frac{V_L^*(g^*, \gamma^*) - V_H^*(g^*, \gamma^*) - \underline{\rho} - \lambda}{\bar{\rho} - \underline{\rho}} \tag{19}$$

$$\frac{1}{\eta} = \theta V_H^*(g^*, \gamma^*) + (1 - \theta) V_L^*(g^*, \gamma^*) \tag{20}$$

BGP: A numerical example



Link to the empirical part

- Note that on the BGP, product innovation is proportional to the skill-complementing technology in the economy, and process innovation is proportional to the skill-replacing technologies in the economy.
- The final good production function on the BGP as

$$Y_t^* = {N_t^*}^{\frac{2\alpha-1}{\alpha}} [{N_{L,t}^*}^{1-\alpha} L^\alpha + {N_{H,t}^*}^{1-\alpha} (\mu H)^\alpha]^{1/\alpha}.$$

- The ratio of product innovation to process innovation as

$$\frac{PD}{PC} \equiv \frac{\Delta N_t^*}{\gamma^* N_{H,t}^*} = \frac{g^* \chi_L^*}{\gamma^* (1-\chi_L^*)^2} \frac{N_{H,t}^*}{N_{L,t}^*}$$

Comparative Static Analysis

	g^*	γ^*	w_H^*/w_L^*
Process innovation becomes more expensive ($\lambda \uparrow$)	$\downarrow$	$\downarrow$	$\uparrow$
Product innovation becomes more expensive ($\eta \downarrow$)	$\downarrow$	$\downarrow$	$\downarrow$
Product innovation becomes more skill-complementing ($\theta \uparrow$)	$\downarrow$	$\uparrow$	$\uparrow$

Extension 2: multiple industries

- Motivation
- Two industries: "manufacturing" (M) and "sales" (S)
- Low-skilled workers can move between industries freely
- Product innovators cannot choose which industry to enter (a simplification)

$$\sigma_M \theta V_{M,H,t} + (1 - \sigma_M)\theta V_{S,H,t} + (1 - \theta) V_{L,t} = \frac{1}{\eta} \tag{21}$$

BGP condition in Extension 2

- Three equations and three unknowns (g, γ_M, γ_S)

$$\frac{1}{\eta} = \sigma_M \theta V^*_{M,H}(g^*, \gamma^*_M, \gamma^*_S) + (1-\sigma_M)\theta V^*_{S,H}(g^*, \gamma^*_M, \gamma^*_S) + (1-\theta) V^*_L(g^*, \gamma^*_M, \gamma^*_S), \tag{22}$$

$$\gamma^*_M = \frac{V^*_L(g^*, \gamma^*_M, \gamma^*_S) - V^*_{M,H}(g^*, \gamma^*_M, \gamma^*_S) - \underline{\rho}_M - \lambda_M}{\bar{\rho}_M - \underline{\rho}_M} \tag{23}$$

$$\gamma^*_S = \frac{V^*_L(g^*, \gamma^*_M, \gamma^*_S) - V^*_{S,H}(g^*, \gamma^*_M, \gamma^*_S) - \underline{\rho}_S - \lambda_S}{\bar{\rho}_S - \underline{\rho}_S} \tag{24}$$

Comparative Statics: Extension 2

	γ_M^*	$w_{M,H}^*/w_{M,L}^*$	$Share_{M,L}$	γ_S^*	$w_{S,H}^*/w_{S,L}^*$	$Share_{S,L}$
Process innovation becomes more expensive in Manufacturing ($\lambda_M \uparrow$)	$\downarrow$	$\uparrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\uparrow$
Process innovation becomes more expensive in Sales ($\lambda_S \uparrow$)	$\uparrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\uparrow$	$\downarrow$

Two caveats

1. The interdependence in the model between manufacturing and sales is not explicitly captured in the empirical exercise.
2. In the model, product innovation always occurs before process innovation
   - PD declines → wages of high-skilled workers decrease → reduces firms incentive to engage in PC.
   - PC moves together with PD, in the same direction
   - the relation is much weaker in the data.

Calibration

- “Manufacturing” (M) and “Wholesale and retail trade” (S)
- UK in 2014 and 2018
- The main purpose of this exercise is to use the observed labour market information and product and process innovation, to recover the unobserved costs of these innovations, and the likelihood of a new product being “non-routine”.

Targets

Variable	2014		2018		Targeted
	Data	Model	Data	Model	
g	0.22	0.23	0.28	0.28	Yes
γ_1	0.17	0.15	0.24	0.24	Yes
γ_2	0.08	0.09	0.14	0.14	Yes
$w_{M,H}/w_{M,L}$	1.34	1.36	1.22	1.25	Yes
$w_{S,H}/w_{S,L}$	1.45	1.43	1.35	1.33	Yes
$Share_{M,L}$	0.49	0.53	0.50	0.54	Yes
$Share_{S,L}$	0.52	0.49	0.51	0.49	Yes
L_M	1.13	1.34	1.10	1.32	No
L_S	1.83	1.63	1.79	1.57	No

Results

Externally determined parameters

Parameter	2014	2018	Source
Elasticity of substitution, α	0.8	0.8	Christopoulou and Vermeulen (2008)
High-skilled workers in Manufacturing, H_M	0.87	0.90	The Structure of Earnings Survey
High-skilled workers in Wholesale and retail trade, H_S	1.17	1.25	The Structure of Earnings Survey
Low-skilled workers, L	2.97	2.89	The Structure of Earnings Survey
Share of Manufacturing firms, σ_M	0.41	0.40	The Community Innovation Survey
Process innovation cost shifting parameter for Manufacturing, λ_M	0	0	Normalization
Process innovation cost shifting parameter for Wholesale, λ_S	0	0	Normalization
The discount rate, β	0.96	0.96	Business cycle literature

Recovered parameters using the calibration procedure

Parameter	2014	2018	Target
The inverse of the cost of product innovation, η	0.183	0.218	The rate of product innovation
The probability that a new product is "non-routine", θ	0.777	0.873	The rate of PC, Skill premium and labour income share
The lower bound of process innovation cost in Manufacturing, $\underline{\rho}_M$	0.006	0.003	The rate of PC, Skill premium and labour income share
The upper bound of process innovation cost in Manufacturing, $\bar{\rho}_M$	0.018	0.610	The rate of PC, Skill premium and labour income share
The lower bound of process innovation cost in Wholesale, $\underline{\rho}_S$	0.183	0.081	The rate of PC, Skill premium and labour income share
The upper bound of process innovation cost in Wholesale, $\bar{\rho}_S$	1.311	2.401	The rate of PC, Skill premium and labour income share
The relative productivity of high-skilled workers, μ	1.363	1.238	Skill premium and labour income share

Some interesting trends recovered

1. The cost of product innovation reduced by about 16% between 2014 and 2018.
2. The chance that a new product requires high-skilled worker to implement (i.e., being non-routine) increased by about ten percentage points, from 77.7% to 87.3%.
3. The average cost of process innovation increased in both industries and it also becomes much more diversified.
4. The relative productivity of high-skilled workers decreased by about nine percent.

Conclusion

- The composition of innovation vs. the amount of innovation
- Product innovations $\longrightarrow$ skill-complementing
- Process innovations $\longrightarrow$ skill-replacing
- A model to illustrate the interaction between the two types of innovations and the labour market
- Uncovered some interesting trends in the UK
- Limitations
  - intensive margin